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Measurement of material properties related to self-healing based on continuum and micromechanics approach

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Measurement of material properties related to self-healing based on continuum and micromechanics approach

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Dedication

To my parents and brother

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Abstract

Measurement of material properties related to self-healing based on continuum and micromechanics approach

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The ability of an asphalt mix to heal is an important property that influences the overall fatigue performance of the mix in the field. Micro damage healing in an asphalt mix is a function of several factors such as the physical and chemical properties of the binder, properties of the mixture, level of damage prior to the rest period during which healing occurs, duration of the rest period, temperature, and pressure. This thesis presents details from a two-part study that addresses the following aspects. In the first part of this study, a DSR based test method was developed to measure inherent healing in asphalt binder and a modified form of the Avrami equation was used to model it. In the second part of this study, an experimental and analytical method based on viscoelastic continuum damage theory was developed to characterize the healing in an asphalt composite (fine aggregate matrix) as a function of the level of damage prior to the rest period and the duration of the rest period. The intrinsic healing of three different asphalt binders was measured at three different temperatures and two aging conditions and it was further demonstrated to be the sum of two components: instantaneous strength gain immediately upon wetting and time dependent strength gain. The intrinsic healing results obtained from the DSR tests were demonstrated to be in agreement with the hypothesis that time dependent intrinsic healing increases with an increase in temperature and decreases with aging of the asphalt binder. The overall healing was measured in four different fine aggregate matrix (FAM) asphalt mixes and various tests were performed to quantify overall healing at isothermal and short term aged test conditions. Additionally two different verification tests were also conducted to demonstrate that the percentage healing measured using the proposed method are independent of the sequence of loading or rest periods. Finally, the overall healing results were demonstrated to support the hypothesis that the healing characteristics determined using the proposed test method can be treated as a characteristic material property.

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Chapter1: Introduction

Every year, nations around the world construct new pavements and rehabilitate millions of miles of existing pavements to address the needs of an ever increasing traffic volume. Evaluating and predicting the fatigue performance of pavements, one of the most important distresses in flexible pavements, will help economically optimize this whole operation. Extensive research effort during the past two decades has concluded that a thorough understanding of the self-healing phenomena and its beneficial effects has a profound impact on the accurate characterization of fatigue crack resistance in flexible pavements and eventually on the methods used to design these pavements and materials.

Fatigue damage in asphalt mixtures is defined as the growth or accumulation of cracks under the action of repetitive loading. These cracks initiate as micro-cracks, which later coalesce to become macro-cracks under the action of a resultant stress/strain field caused by repeated loading (Little et al., 2001). Accumulation of these macro-cracks reduces the effective load bearing area in the bulk of the material, resulting in the reduction of overall stiffness of the matrix. As the functionality of the pavement, as a load bearing structure, is compromised due to repeated loading, it is important, from the perspective of pavement performance, to characterize the fatigue life and factors affecting the fatigue life of a pavement.

Early attempts at characterizing fatigue were made using the relationship between drop in stiffness and number of loading cycles. These relationships were obtained by performing continuous loading tests on asphalt mixes which closely represented the field mix. However, the use of shift factors (Lytton et al., 1993) to predict field response based on laboratory results, provides sufficient evidence that the fatigue life formulated using the results from accelerated laboratory tests, discount the beneficial effects of several factors such as lane wander, rest periods, structural and climatic effects acting on a pavement during its service life. A mechanistic model which takes into account realistic loading conditions and beneficial effects of different field conditions affecting the pavement performance is desired to better assess the pavement performance.

Lee and Kim (1998) described that the factors affecting fatigue damage modeling can be broadly categorized into three components: linear viscoelasticity, fatigue damage and healing. Healing was referred to as a combination of different mechanisms, apart from linear viscoelastic relaxation, which contributed to recovery of stiffness or strength gain during a rest period. Unlike relaxation, healing can be directly correlated to any observed field conditions which beneficially affect the fatigue life. Therefore, in order to characterize fatigue damage based on prevalent realistic pavement conditions, it is necessary to accurately characterize micro-damage healing.

Micro-damage healing is defined as partial or complete reversal of micro-crack growth during a rest period devoid of any form loading (Kim et al., 1997). Micro damage healing in an asphalt mix is a function of the constituent binder's chemical and physical make up, level of damage prior to the rest period, duration of the rest period, mixture properties such as gradation, binder content, air voids and other external factors such as temperature. Healing is most commonly quantified in terms of the percentage gain in the number of load cycles to failure or gain in the modulus after a rest period (Bazin and Saunier, 1967, Raitby and Sterling, 1970, Kim, 1988, Tayebali et al., 1994, Kim et al., 2003, Maillard, 2003). However, a drawback of this approach is that the percentage healing reported is a function of the rate and type of loading and does not address the mechanisms causing it, rendering it useful only in the context of the specific test conditions. There is a need to better understand mechanisms that drive healing and also measure fundamental material properties related to healing that are independent of loading and test conditions. One of the broad objectives of this research is to investigate and measure material properties required to develop constitutive relations which can be used to model healing. A healing model can be incorporated into a comprehensive fatigue-healing damage model which predicts pavement performance irrespective of test conditions.

More specifically, the research presented in this thesis was conducted to: (1) develop and summarize an improved method to measure inherent healing in asphalt binder , (2) provide evidence and quantify the change in inherent healing characteristics with temperature and aging of the asphalt binder, (3) develop a new method to quantify overall healing based on viscoelastic continuum damage theory, with the secondary objective of quantifying healing independent of loading characteristics, (4) validate the test method and loading conditions by demonstrating the results obtained from quantifying overall healing as artifact free and independent of loading conditions.

Even though the healing model developed in this study is based on asphalt binder and fine aggregate mastic (FAM) tests, the theory and procedure developed is general enough to be applied to full asphalt mixes. Also the continuum damage theory, which forms the core of the overall-healing model, can be used to account for several other forms of damages such as, thermal cracking and moisture induced damage, provided such processes exhibit insensitivity to path of loading in the formulation of total work required to induce damage in the material.

This thesis is divided into the following five chapters. This first chapter provides an introduction to different aspects of healing along with an emphasis on the objectives and needs addressed in this research. The second chapter summarizes the literature review of research related to the two major aspects of this thesis: (1) experimentally measuring intrinsic healing with an emphasis on effects of temperature and aging (2) quantifying overall healing in fine aggregate asphalt mixes based continuum damage approach. The third and fourth chapters present details on the background theory used in developing the experimental framework along with the results from tests conducted on different binders and fine aggregate mastic (FAM) samples. Chapter five presents the conclusions drawn from the research work done along with a scope for future work.

Chapter 2: Literature Review

The importance of healing and consequently fatigue performance of asphalt mixtures has been recognized by many researchers. Significant work ranging from identifying mechanisms to development of novel experimental methods to quantify healing and fatigue in asphaltic materials has been done in the past two to three decades. For contextual clarity behind the research done so far, this chapter is divided into three sections. The sections are:

- evidence and theories demonstrating the occurrence of healing in asphaltic materials,
- hypothesized healing mechanisms (the focus of which is primarily to build the case around intrinsic healing),
- and, experimental studies and efforts to quantify fatigue and overall healing in asphaltic materials.

It is important to note that some of the concepts used in determining the mechanisms governing the healing phenomena and fatigue damage are inspired from an established and extensively studied field of polymer research and elastic material fatigue characterization respectively. It is recognized that at nano-scale the mechanisms may be different but at micro-scale (the scale of interest in this study) the phenomenological understanding of self-healing polymeric materials can guide the understanding of similar such processes in asphaltic materials. As a result the reader might sometimes find a digression of discussion from asphaltic material to other materials which will help elucidate the concepts in a broader sense.

2.1 Evidence of Occurrence of Healing

Among the earliest work reporting the beneficial effects of introducing rest periods during fatigue tests was the work done by Bazin and Saunier (1967). The objective of their study was to understand behavior of pavements under realistic loading conditions. Monotonic tensile tests and cyclic fatigue tests were reportedly performed to completely break beam samples of different asphalt mixtures followed by rest periods ranging from 1 - 300 days. It was noted that these rest periods along with regulation of pressure and test temperature across the damaged surface beneficially affected the fatigue performance of mix, as an increase of about 90 percent in tensile strength ratio was observed with just three days of rest period at 25 degrees Celsius for an ordinary dense-graded mix. Their research clearly showed the occurrence of healing or healing-like phenomena (viscoelastic relaxation) in asphalt pavement and factors such as duration of rest, extent of damage prior to rest periods, test temperature and pressure, type of aggregate and binder affect the healing ability of mix. However the results featured in their study were to be appreciated with a caveat that the pressure and duration of rest periods applied as test conditions are unrealistic and probably would not occur in field, therefore concluding that for accurate and usable measurements emphasis must be placed on measuring healing in partially ruptured specimen with many micro-cracks and not really on fully ruptured specimen. Many such similar studies conducted around that decade by various researchers such as pulsed loading tests reported by Raithby and Sterling (1970), rotating bending fatigue tests by McElvany and Pell (1973), three point bending beam fatigue tests by Bonnaure (1982) to name a few, presented with a similar set of findings that on provision of a rest period there is a definite improvement in fatigue life of mixture due to healing or healing-like phenomena.

Some of the recent and most significant experimental work directed to substantiate the occurrence of healing, and most importantly to develop feasible means to quantify healing was done by Little et al. (2001), Kim (1988) and Kim et al. (1990). These studies included an extensive literature review ranging from works done in the field of polymer healing to works done on fatigue/healing characterization in asphalt pavements. Innovative methods to quantify healing using indicators such as the decrease in dissipated energy, gain in stiffness, and developing constitutive damage-healing models are a few of the highlights of these studies. Little et al. (2001) demonstrated that inclusion of rest periods (up to 24 hrs.) doubled the fatigue life of beams tested in flexure. Kim (1988) demonstrated that an increase in the duration of the rest period introduced during a three point beam fatigue test corresponded to an increase in the pseudo strain energy indicating occurrence of the healing phenomenon. Furthermore evidence from tests conducted by Bhairampally et al. (2000) in conjunction with the earlier works done by Bazin and Saunier (1967) suggested that maximum healing is achieved when the rest periods are provided before infliction of extensive damage, suggesting that healing in micro-cracks is more prominent than in macro-cracks. This was done by introducing hydrated lime as filler material which resulted in crack pinning and improved healing as the damage evolution was restricted to micro-cracks. Additional studies conducted by Carpenter and Shen (2006), Kim and Roque (2006) and by Maillard (2004) also delineate the beneficial effects of rest periods, a summary of these studies will be presented in detail in the coming sections as they are more relevant in the section of literature review which presents different methods developed to quantify healing. An extensive and detailed review of work done in the field of healing in asphalt binder and mixes is presented in the article by Little and Bhasin (2007).

Apart from these laboratory findings, probably the most convincing field evidence is provided by the work done by Williams et al. (2001) and Nishizawa et al. (1997). Williams et al. (2001) used surface wave measurements to gauge the stiffness of four pavement sections with different thickness and types of asphalt layers on a homogenous subgrade, built at Turner Fairbanks accelerated loading facility (ALF). The surface wave measurements were taken both immediately after loading and again after 24 hrs. Irrespective of type of pavement, the stiffness measurements showed an increasing trend with the highest increment obtained at the center line. William et al. (2001) also reported similar findings in healing trends measured using surface wave analysis at Mn/ROAD pavement sections on US highway 70 in North Carolina. Nishizawa et al. (1997) used this data to demonstrate that micro-damage healing offsets the occurrence of fatigue cracking at low strains resulting in no visible occurrence of damage.

Performance prediction, as mentioned earlier, is an operation with a profound economic implication. The study conducted by Lytton et al. (1993) for SHRP was one of the major steps towards understanding the reasons behind shift factors and their applications in field predictions. A significant part of shift factors, which are used to scale the laboratory based predictions to match field conditions, was determined in their study. It was claimed and later verified that rest periods between loading cycles which contributed to micro damage healing and residual stress state along with dilation stresses resulting from a triaxial stress state, are the two major field factors which were not duplicated in laboratory tests and thereby contributing significantly to an increase of the shift factors. Lytton et al.(1993) speculated that healing ensuing the rest period was the most significant of the two factors and also proposed a relationship between shift factor and number of cycles to fatigue failure which gives fairly accurate predictions.

2.2 HYPOTHESIZED HEALING MECHANISMS

Despite the best efforts, validity of the field predictions based on continuous fatigue laboratory studies is questionable as the shift factors used in linking them is always specific to loading and test conditions. In other words, applicability of empirical predictions is limited, as it is necessary to first map the material behavior to different types of loading and test conditions in order to predict the fatigue performance of an asphalt mixture under the action of any type of loading and test conditions. Understanding the mechanism behind healing coupled with an understanding of the physics behind this phenomenon, would be one analytical way apart from continuum scale modeling to quantify healing and incorporate them into predicting the field performance. Polymer healing and its mechanisms was the object of intense study well before healing in asphalt binder and/or mixes was considered. One definition of healing in polymers is given by Prager and Tirell(1981):

"When two pieces of the same amorphous polymeric material are brought into contact at a temperature above its glass transition, the junction surface gradually develops increasing mechanical strength until at long enough times the full fracture strength of the virgin material is reached. At this point the junction surface in all respects becomes indistinguishable from any other surface that might be located within in the bulk material we say the junction has healed."

The above definition describes the effect of molecular interactions occurring across the crack surfaces before, during and after contact. Wool and 'O Connor (1981) identified these phenomena and discretized them into the following, based on the sequence of occurrence: (1) surface rearrangement (2) surface approach (3) wetting (4) diffusion (5) randomization. The strength gain, which is a measure of overall healing in mechanical tests, is actually the combined outcome of steps (3), (4) and (5), making it imperative to first understand the underpinnings behind these steps. Wetting (step 3) or surface attraction is primarily a function of surface energy and is marked by instantaneous gain in strength due to work of cohesion. Intrinsic healing, a time dependent function, which is either measured by an increment in energy or strength or any other fracture mechanics properties is defined as the process of self-diffusion of random coils of molecules followed by randomization over time, in effect it is the combination of steps (4) and (5). De Gennes (1971) proposed a "reptation" model to explain the self-diffusion phenomena according to which the polymeric molecule move in worm-like fashion inside the tube-like gel matrix made of other molecules. The movement of these chain molecules is associated with a very high frequency but small amplitude back and forth motion along the centerline of a hypothesized tube, a contention which was later verified by Berger and Kramer (1987) based on the disentangled time for chains in reverse healing or damage process. Based on these findings it can be speculated that a molecule with lesser branching and a linear chain like structure will diffuse to a longer distance in the same time as compared to molecules with more branching of similar length. Works done by different researchers demonstrated the validity of this speculation, a summary of which is presented below.

Different asphalt binders contain different percentages of small chains, longer but lesser branched chains and longer branched chains. Based on this it can be expected that different asphalt binders will have different molecular rearrangement capability which might affect rearrangement across the wetted crack interface and therefore rate of healing. Also the extent of diffusion and eventually healing is a function of many factors such as molecular weight, temperature, pressure and rest periods. Work on factors affecting diffusion is therefore understandably important from the stand point of constitutive modeling of binder. Kim et al. (1990) used FTIR to measure methylene to methyl ratio and MMHC (methyl and methylene hydrogen atoms to methyl and methylene carbon atoms) and investigate their effects on healing in asphalt binders. It was concluded that a higher methyl to methylene ratio when compared to MMHC would indicate longer polymer chains with less branching and is desirable for facilitating healing as hypothesized by Wool and O'Connor (1981). These works were later built upon by Little and Prappnachari (1991) who reported another important fact that the same ratio used by Kim (1990) is also an indicator of viscoelastic relaxation properties of asphalt binder. Viscoelastic recovery takes place primarily at a molecular scale and is primarily due to short range movement of molecule. Healing on the other hand has the same mechanical effect but occurs at a nano or micrometer-scale, thus any mechanical measurement based on fatigue tests will inevitably measure a compound effect of both relaxation and healing. The method of quantifying intrinsic healing and overall micro damage healing presented in this thesis measures is designed to account and successfully differentiate the viscoelastic relaxation from chemical healing in the asphalt binder/ mix.

The temperature dependence of diffusion, another important aspect required for constitutive modeling, has also been studied by many researchers. Jud and Kausch (1979) measured the increment of fracture toughness in healed specimen under different temperature conditions by performing a “penetration” test on asphalt mixture beams. Wool (1980) developed diffusion master curves with the goal of superposing them to formulate a master diffusion curve with the temperature. More recently the computer aided simulations done by Greenfield and Zhang (2007) on molecular movements within the bulk at five different temperatures also illustrate the sensitivity of diffusion to temperature. However it is important to note that molecular diffusion defined in this study is not the same as that defined in the thesis of Wool (1980) and it is mentioned here only to emphasize the point that temperature has a profound effect on molecular movement which might be within the bulk or at the surface of the material.

2.3 EXPERIMENTAL STUDIES AND EFFORTS TO QUANTIFY FATIGUE AND OVERALL HEALING IN ASPHALTIC MATERIALS

Overall healing can be defined as the reversal of micro-damage. Any parameters or quantities used to measure fatigue damage would be the primary choice of parameters to use in quantifying healing. The most commonly used quantities in characterizing fatigue/healing are number of cycles to failure (extension of fatigue life), increment in stiffness (any form of modulus), and other energy methods. The conventional procedure to measure healing is to measure percentage gain or simply gain in values of either of these parameters post rest periods, which are provided in a cyclic fatigue loading. This section is further divided into three sub sections, the first two sub sections list different methodologies employed in measuring healing either through energy based or through non-energy based quantities. The final segment provides the summary and an argument to demonstrate the viscoelastic elastic continuum damage method as the preferred method over other techniques along with a discussion on shortcomings of the techniques previously used and developed.

2.3.1 Energy based methods

Crack initiation and crack propagation are the two steps, occurring sequentially, which contribute to the evolution of fatigue damage in asphaltic mixtures. This hypothesis was extensively reviewed and skillfully demonstrated as two distinct phases of damage in the work done by Lytton et al. (1993). It was shown that the controlled strain mode of fatigue loading resulted in only "crack initiation" at multiple locations within the bulk of a tested asphalt mixture beam with no clear follow up of propagation, whereas in the controlled stress mode of loading, damage evolution clearly showed both the stages of initiation and propagation occurring sequentially. Even though the fracture properties governing the damage evolution are the same for both modes of loading, phenomenological correlation of fatigue life based on stiffness often requires the knowledge of mode of loading, rendering any fatigue life measurements based either on strain amplitude or on amplitude and initial stiffness valid only in specific loading and test conditions such as mode of loading, amplitude of loading , frequency of loading and other conditions such as temperature and pressure, for a given material (Tayebali et al. ,1994).

To address the issue of mode dependency, early investigative efforts focused on the use of dissipated energy as an indicator instead of stiffness. However it was demonstrated through extensive research (Bhasin et al., 2008) that the direct use of dissipated energy alone will not address the problem, as total energy is the sum of both viscoelastic energy and incremental fatigue energy and the viscoelastic energy is dependent on the loading criterion. Carpenter and Shen (2006) proposed that it is not the total dissipated energy but the relative change in the dissipated energy that contributes towards the damage evolution, therefore making it a more apt contender to measure and characterize fatigue or healing. Four point beam fatigue tests were first conducted to demonstrate that the plateau value (PV) defined as the magnitude of the ratio of dissipated energy (REDC) value at 50 percent of initial stiffness, has a unique linear relationship with the number of load cycles for any asphalt mix irrespective of mode or amplitude of loading. A higher magnitude of PV indicates a higher reduction in damage energy and a shorter fatigue life. To account for healing, rest periods of duration 1-9 seconds were introduced after every load cycle and the decrease in the value of PV measured. This drop in PV can then be converted into gain in number of cycles using the PV-load cycle relationship for a given mix or can be used to demonstrate the extension of the so called “fatigue endurance limit”. A similar approach was adopted by Kim and Roque (2006) to measure healing in terms of recovered dissipated creep strain energy and by Pronk et al. (2006) to develop and calibrate a partial healing model based on four point beam fatigue tests.

Apart from mechanical energy based healing models, research on finite element schemes based on thermodynamic potentials and free energy conservation used to quantify healing are currently being developed. Work done by Kringos et al. (2009) demonstrated the efficacy of one such approach through preliminary results from 3-dimensional bitumen healing simulations using a “phase-field” model. In their study, it was speculated that the asphalt binder was made up of phases with different stiffness and the interface bonds are most likely to be broken under the action loads due to high stress concentration in the interface region. Healing was defined as reformation of these interface bonds and it was modeled by varying a few “kinetic” parameters (temperature, pressure) in the transport equation formulated from mass and free energy conservation principles. Finally it was hypothesized that these binder phase measurements can be incorporated on a continuum scale by using an elasto-visco-plastic energy model. Even though the work in this area is at very nascent stage, the approach of using a constitutive behavior of healing in asphalt binder and mixtures is quite noteworthy and resourceful.

2.3.2 Other parameters (stiffness, load cycles and healing indices)

The most common and among the earliest methods developed to quantify healing is by measuring the gain in number of load cycles to failure (NF) by incorporating one or more rest periods during a fatigue test and with reference to the original NF measured without rest periods. This method of increment in NF is a simple yet powerful tool for qualitative analysis; it can directly help the designer to select a mix that has better healing potential. Usually the NF is either defined as cycles to complete failure or number of cycles until the stiffness reaches a preset value. Early works done by Raitby and Sterling (1970), McElvany and Pell (1973) and Bonnaure et al. (1982) quantified healing as a percentage gain in number of cycles to failure with the only difference to be found in the method and mode of load application. Kim (1988) demonstrated the use of three different variations in analyzing the increment in the number of cycles to characterize the differences between the healing potential of two asphalt mixes. In the first method a simple percentage increase in number of cycles to failure (NF) was calculated based on increment in NF from samples subjected to rest periods with reference to NF from control tests with no rest periods. In the second method to eliminate the issue of different NF’s in different specimen of the same mix for control tests, an indicator for the level of damage was developed. The damage 'indicator' used, was defined as the ratio of number of load cycles a specimen endured until the provision of rest period to the number of cycles required to reduce the stiffness until failure of the same specimen, measured without inclusion of rest period. In the third method healing was measured as the ratio of number of cycles of loading applied to a sample before its stiffness decreases to the value it had before the rest periods with NF of the same sample. If multiple rest periods are provided a cumulative is taken and then normalized by total NF. It was observed that following any of these methods a clear difference in healing potential can be seen between the two mixes, however the percentage gain reported in all three methods are quite different from one another. Kim (2003) used a dynamic mechanical analyzer (DMA) to predict the increment in shear fatigue load cycles on fine aggregate matrix (FAM) samples using similar approaches as mentioned above.

Measuring increment in stiffness is another popular means of quantifying healing. Early work done by Bazin and Saunier (1967) used increment in tensile strength ratio of the specimen before and after rest periods to quantify healing. Other more recent works include the work done by Lee and Kim (1998), Maillard (2003) and Williams et al. (2001). Williams et al. (2001) described uniaxial cyclic fatigue tests which quantified healing as a percentage increase in dynamic modulus. In the later segment of the study the concept of healing index originally developed by Kim. (1988) was modified to use phase change measurements instead of pseudo dissipated energy measurements and quantified healing in test sections at ALF. Maillard (2004) et al. used ultrasonic pulse waves to measure the recovery in stiffness and calculated healing. Tensile tests were performed on asphalt binders lodged between glass spheres which are intended to simulate the aggregates in an asphalt mixture. Post fracture a rest period is allowed during which ultrasonic pulse waves are transmitted to measure the increment in stiffness at regular intervals. Detection of an increase in amplitude of the ultrasonic wave at the receiving end of the sample indicates an increase in stiffness, which implies occurrence of healing. Lee and Kim (1998) used a gain in flexural stiffness after the rest period in comparison with flexural stiffness just before the onset of rest period.

2.3.3 Summary and use of VECD theory

Most of the aforementioned methods which are used to assess healing are generally phenomenological in nature and don't account for the mechanisms that drive healing in asphalt. Any measurement of a decrease or increase in stiffness is by default a function of input load amplitude or magnitude, a higher amplitude results in a faster decrease irrespective of the mode of loading (controlled strain or stress) as a higher amount of damage is inflicted. Therefore healing measured as a function of stiffness is indirectly dependent on load amplitude. Similar such arguments can be made for healing quantified as a function of other parameters such as an increment in dynamic modulus (function of loading frequency), dissipated energy (function of stiffness and therefore on loading amplitude) and increment in load cycles (dependent on both amplitude of loading and mode of loading). This type of phenomenological measurement of healing will limit its use to provide the user only with the means of qualitatively comparing healing in different asphalt mixes and not with a universal quantity dependent only on material properties and external factors such as temperature and pressure. Besides this drawback, phenomenological quantification also is quite expensive as a user cannot use the fatigue data of a particular mix with one set of test conditions to predict another set of conditions, implying that more tests have to be conducted for gauging the behavior.

Mechanistic modeling of asphaltic material, unlike empirical studies, has the capability to unify multiple phenomena and predict the net effect of healing during a rest period over a wide range of conditions given an input from few simple tests. Developing a constitutive model addressing healing phenomenon and the factors affecting it, in conjunction with the framework developed by Wool and O'Connor requires the measurement of intrinsic healing (a combined effect of both diffusion and randomization) and overall healing. It is important to note that intrinsic healing in asphalt binder cannot be modeled on similar lines as polymers, as the molecular structure in asphalt binders is different from the polymer chain type structure considered by Wool and O'Connor. To suitably represent, healing in asphalt binder and eventually in asphalt mixture, Bhasin et al. (2008) developed a new modified healing framework similar to the one developed by Wool and O'Connor. According to this new framework measuring intrinsic healing and the influence of extraneous conditions on it, can be done either through molecular simulations or through mechanical healing experiments designed to censor out the effects of wetting. A portion of the work presented in this thesis adopted the DSR based technique formerly developed by Bommavarm (2009) with the goal of improving the robustness in measuring near zero time strength gain and to quantify the effects of temperature. More details of the procedure and theoretical considerations are presented in chapter 3.

Overall healing (combined effect of wetting and intrinsic healing) is typically measured by inducing damage to an intact specimen followed by measurement of the rate at which strength or stiffness is regained over time, but as mentioned earlier, traditional methods to quantify healing are useful only in qualitatively determining the relative propensity of an asphalt mix to heal as the results are highly dependent on the loading characteristics. To address this issue a method to measure healing based on viscoelastic continuum damage principle is developed and presented in this study. Recent studies demonstrate that the use of viscoelastic continuum damage theory (VECD) in fatigue characterization of an asphalt concrete mix successfully accounts for the rate dependent damage growth independent of the specific mode of loading or test conditions. VECD theory relates the reduction in stiffness under fatigue loads to an internal state variable, S, that represents the overall damage within the specimen. This internal state variable is related to the loading and stiffness by a damage evolution law. The closed form relation between pseudo stiffness (C) and a damage parameter (S) was demonstrated to be independent of loading characteristics and unique for a particular mix. Using this unique closed form relation, healing ensuing from the rest periods is measured as an increment in the damage parameter (S) as opposed to the conventional increment in stiffness (C) . Verifications tests were designed and performed to demonstrate that the results obtained are artifact free while supporting the objective of measuring healing as a function devoid of any influence from loading conditions.

The general approach of applying VECD essentially consists of (i) building a constitutive model based on the mechanisms such as linear viscoelasticity, fatigue damage and micro damage healing that asphalt specimen exhibit under the influence of loads, (Kim 1998), (ii) calibrate the model to the material properties (iii) finally, develop predictions based on the new calibrated model. The linear viscoelastic part of the response is accounted for by transforming the stress strain data into the “pseudo” domain using the correspondence principles (CP) introduced by Schapery (1984). Using CP’s the time effect of viscoelastic relaxation or creep can be removed from the total response and the remainder stress/pseudo strain data can be classified purely as the damage evolution and recovery response of asphalt specimen under damage loading. Earlier versions of the VECD theory used only linear viscoelastic theory and assumed all other departures to be damage causing while current versions account for non-linear responses as well, which usually, is the dominant behavior under extreme loading conditions (Schapery, 1997).

The work potential theory developed by Schapery (1990) is a continuum damage theory which describes a method to predict the mechanical behavior of elastic material under incremental damage using thermodynamic principles. This theory provides a method to formulate the total mechanical work done on a material with growing damage. It utilizes the concept of strain energy potential and energy due to the change in the thermodynamic internal state variable (ISV) as the total energy required by the material to change strain and thermodynamic state. Using the hyper-elastic model the value of stress can be predicted by differentiating the total work derived as a potential of strain (change in ISV's are formulated as functions of strain) with respect to strain. The damage parameter developed by Schapery(1981) based on a power law of crack growth is used as the representative ISV in many previous studies (Park, 1996, Kim, 1998). The theory does not differentiate between the type of damage but simply relates the net effect of damage with reduction in stiffness. Using this VECD formulation, healing was successfully quantified as the gain in pseudo stiffness in many research works. Little et al. (2001), Kim et al. (1988, 90, 98) and Park et al. (1996, 1997) performed various types of tests such as cyclic shear, uniaxial monotonic, uniaxial cyclic (push pull) and four point beam bending and successfully obtained a constitutive healing function based on stress-pseudo strain response. A detailed review of this theory along with how it can be used in tandem with the CP's to generate a damage constitutive model is presented in chapter 3.

Chapter3: Theory, Background and Procedure

An introduction to the mechanism behind the healing process as hypothesized by Wool and O' Connor which is adopted in this study is as follows. The process of closure of a cracked surface due to mechanical properties of the material such as viscoelastic relaxation and flow, along with the influence of surface free energy is referred to as *wetting of cracks.* On complete wetting of cracks the interface gains an instantaneous but partial recovery of strength caused due to interfacial work of cohesion amongst the crack surfaces. Crack wetting is followed by an increase in the interfacial stiffness due to rearrangement and randomization of molecules across the closed crack interface; this increase in stiffness is referred to as *intrinsic healing*. This strength gain will continue until the material regains its complete strength or until the onset of damage loading. More specifically, overall self-healing (R (t)) entails reversal of crack opening (referred to as crack wetting, $\phi(t)$) followed by the reversal of micro-damage (referred to as intrinsic healing, $R_h(t)$) that occurred in the failure zone and can be mathematically represented by a convolution integral between the wetting function and intrinsic healing function over the rest or recovery period (t).

$$\boldsymbol{R(t)} = \int_{\tau=-\infty}^{\tau=t} \mathbf{R_h(t-\tau)} \frac{\mathbf{d\Phi(\tau)}}{\mathbf{d\tau}} \mathbf{d\tau} \tag{1}$$

Following this hypothesis it is quite evident that a constitutive relationship should incorporate both the intrinsic healing and wetting models as a function of the material properties.

Determining the intrinsic healing function, which is purely a function of a binder's physical /chemical makeup along with other external factors such as temperature and pressure constitutes the necessary first step to take in developing a material based healing function. This can be inferred based on the important fact that micro-damage healing occurring in an asphalt mix is predominantly contributed by healing of micro-cracks present in the asphalt binder and the fine aggregate mastic fraction of the full mix. Additionally, quantifying intrinsic healing will provide the user with an indicator to measure the propensity of an asphalt mix to heal during rest periods, which can also be used to improve the overall healing ability in a mixture as modifying the asphalt binder, is often easier and more practical than changing the mix design. In this study a refined DSR based method was used to quantify and measure the change in intrinsic healing with temperature and aging conditions. The new procedure developed draws the general idea and theme from the procedure developed previously by Bommavaram et al. (2009) to quantify intrinsic healing. The modifications incorporated in the present method were designed to address the inability of the previous method to make accurate measurements of intrinsic healing values reported at time t=0 (beginning of test sequence). Emphasis is placed on the intercept values (Intrinsic healing vs. time) as they can be related to the work of cohesion of the asphalt binder.

The wetting function as hypothesized by Wool and O' Connor is dependent on crack tip geometry and rate of crack closure. Determining the wetting function for a matrix with cracks dispersed throughout the bulk of the media, with different orientations and cracks opening in different modes of failure, may not be experimentally feasible or required if the objective were to obtain the overall healing response of the composite as a continuum. The simplest means to quantify wetting function and verify it against the theory developed by Schapery is to back calculate wetting by de-convoluting the intrinsic healing function from the measured overall healing. Therefore in order to completely characterize healing potential based on the convolution integral, it is necessary to first quantify intrinsic healing followed by measuring overall healing independent of loading conditions and purely as a function of material properties.

In this study, procedures to measure intrinsic healing and overall healing were developed, but the actual de-convolution to develop the wetting function is yet to be worked on.

Taking into account the obvious differences in the procedures to quantify intrinsic healing and overall healing which occur at different length scales, this section is further divided into two sections:

1. Development of a healing framework and quantifying intrinsic healing using a DSR based test procedure.
2. Quantifying overall healing using viscoelastic continuum damage (VECD) theory.

The first section presents the procedural details of the DSR based experiments used to quantify intrinsic healing as a function of temperature and aging, along with details pertaining to sample preparation. The second section presents the details regarding the use of viscoelastic continuum damage theory, developed from elastic work potential theory (Schapery (1975, 1990), to characterize damage evolution and quantify healing in viscoelastic composite materials. The concept of viscoelastic correspondence principles (Schapery, 1984) necessary to convert the present viscoelastic problem into a reference elastic one is introduced and the formulation of 'Damage Parameter' as the sufficient and required internal state variable (ISV) to represent damage evolution is presented. The test procedure developed to measure overall healing in fine aggregate mastic (FAM) samples along with details regarding the test conditions form the concluding segment of this section.

3.1 QUANTIFYING INTRINSIC HEALING USING A DSR BASED TEST PROCEDURE

As mentioned earlier, Wool and O' Connor (1981) developed a framework which described healing as a two-step process comprised of intrinsic healing and wetting of crack surfaces. In this study an improved experimental procedure was used, which enables the user to measure strength gain across a cracked surface, almost at the instant the two crack surfaces are put together. Based on the results from these tests, the intrinsic healing or strength gain was further demonstrated to be the sum of two components: instantaneous strength gain immediately upon wetting and time dependent strength gain. The Avarami model (equation 3) was used to mathematically represent both parts of the intrinsic healing and the tests conducted at different aging and temperature conditions were used to relate the change in model parameters to change in intrinsic healing as measured. This section is further divided into three sub-sections; sub-section 1 describes the Wool and O' Connors theory which relates intrinsic healing with overall healing, sub-section 2 describes in detail the hypothesized mechanism of intrinsic healing along with its mathematical representation as used in this study and finally sub-section 3 describes the sample preparation and the experimental procedure to measure intrinsic healing.

3.1.1 Theory governing the mechanics of self-healing

The growth of a micro-crack is associated with the creation of new fracture surfaces. A precursor to the growth of a micro-crack is damage in the vicinity of the crack tip. This damage is associated with the deformation and rearrangement of molecules in the failure zone. The mechanism of self-healing can therefore be regarded as a reversal of these processes. More specifically, self-healing entails reversal of crack opening (referred to as crack wetting) followed by the reversal of micro-damage (referred to as intrinsic healing) that occurred in the failure zone. Based on this hypothesis, Wool and O'Connor (1981) mathematically described the rate of self-healing, $R(t)$ as a convolution of two time dependent functions (equation 1), rate of wetting $\phi(t)$ and rate of intrinsic healing $R_h(t)$.

The lower limit of negative infinity in equation (1) has a special significance: it is used to describe healing when there is micro-damage at the crack tip that has not yet advanced to the crack opening stage. In other words, a fracture process zone that has not resulted in crack opening can be considered as partially healed. This is achieved by considering that the crack is closed and partially healed at [illegible]. The rate of intrinsic healing, $R_h(t)$, is dictated by inherent material properties such as surface free energy of the binder, molecular morphology, and extrinsic factors such as temperature (Kim et al., 1990, Wool and O'Connor, 1981, Bhasin et al., 2009). The rate of crack wetting $\phi(t)$ is dictated by factors such as crack geometry, mechanical properties of the binder or the mixture, and the surface free energy of the binder. In summary, the surface and molecular properties of the binder influence the rate of intrinsic healing whereas the mechanical properties of the composite and the binder influence the rate of wetting. By isolating and measuring the rate of intrinsic healing, $R_h(t)$, it is possible to compare the inherent healing capacities of different asphalt binders as well as the influence of factors such as temperature and aging on the inherent capacity of the asphalt binder to self-heal.

Wetting of two faces of crack constitutes the first step of healing and is defined as the process in which two cracked surfaces come in contact with each other. The driving force which causes the parts of crack geometrically close to each other to join and proceed is the inherent surface attraction of the polymer. Following wetting at one point in the crack surface, nucleation along adjacent sides of the crack occurs which grows in size, eventually covering the entire crack surface. A hypothetical representation of wetting as presented by Wool and O' Connors (1981) is presented below in Figure 1.

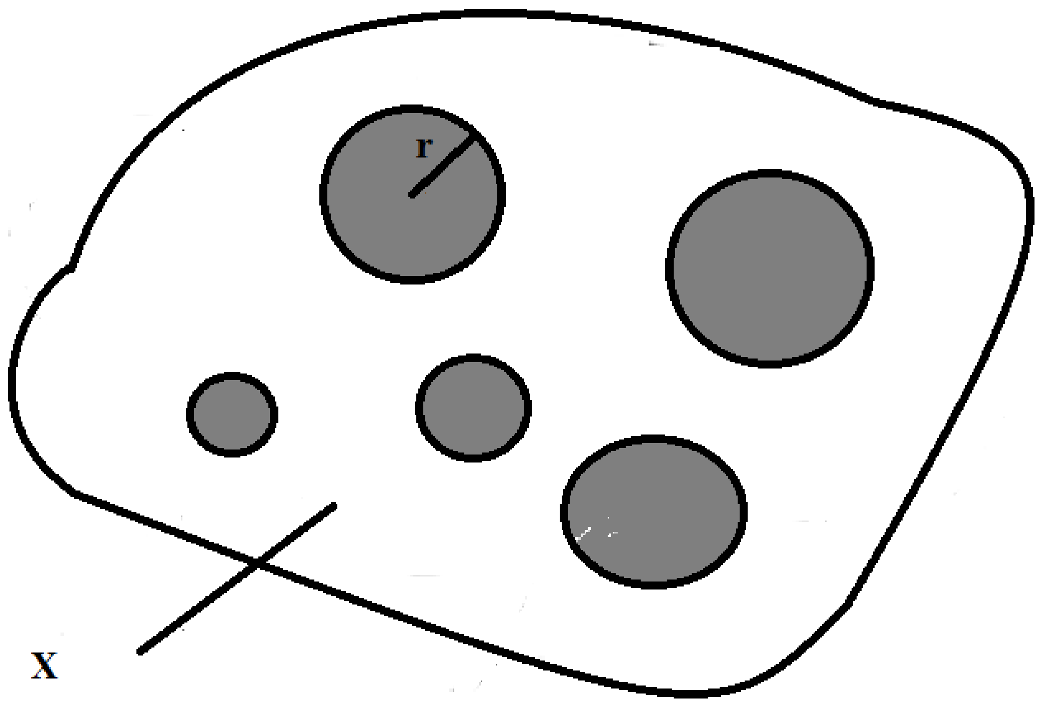

Figure 1: The circular area represents propagation of wetting pools of radius r along the crack interface denoted by quantity X (Adapted from Wool and O'Connor, 1981)

The mathematical representation of the wetting function as developed by Schapery (1989) is given by:

$$\frac{\partial\phi(t,X)}{\partial t} = \dot{a_b} = \beta\left[\frac{1}{D_1 K_m}\left\{\frac{\pi W_c}{4(1-\nu^2)\sigma_b^2\beta} - D_o\right\}\right]^{\frac{-1}{m}} \quad (2)$$

Where W_c is the work of cohesion; ν is the Poisson's ratio; D_o, D_1,and m are creep compliance parameters obtained by fitting $D(t)$ = D_o+$D_1 t^m$; $k_m$is a material constant that can be computed from m and finally the terms, σ_b, β, and $\dot{a}_b$ are as described below in Figure 2 (Source: Schapery(1989)) . From the above equation it is evident that the constant rate at which wetting occurs, is determined purely by mechanical, viscoelastic and material properties of the bitumen.

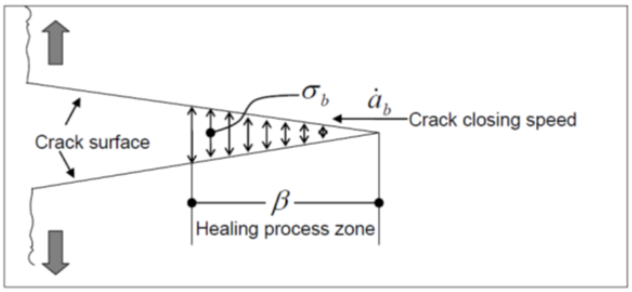

Figure 2: Wetting as hypothesized by Schapery (1989)

Given that both the wetting and intrinsic healing functions are material properties and would behave independent to type of loading, from Equation 1 it can be concluded that the overall healing in the material should also be dimensionless and unique to a particular material and independent of loading.

3.1.2 Intrinsic healing

The intrinsic healing function describes the rate at which the wetted crack interface self-heals over time. Intrinsic healing is a dimensionless quantity that represents the ratio of a mechanical property of interest (e.g. fracture toughness or stiffness) of a wetted crack interface that is undergoing self-healing to the value of the same property in an undamaged material. As mentioned earlier the intrinsic healing or rate of strength gain is comprised of two components: instantaneous strength gain and time dependent strength gain due to reorientation and randomization of molecules across the wetted crack interface. Molecules at the surface (of a crack or otherwise) are distributed and oriented differently from the molecules in the bulk due to the influence of surface free energy. The term randomization and reorientation is used in a relative sense to describe the redistribution of molecules that occurs when the wetted crack surface transforms to the approximate (statistical) configuration of the bulk. Wool and O'Connor related the molecular size and self-diffusivity of molecules to the time dependent healing across wetted crack interfaces. Asphalt binders are comprised of a very complex and heterogeneous ensemble of molecules. Consequently, it is not possible to accurately model the reorientation and randomization of molecules during the time dependent intrinsic healing process. Bommavaram et al. (2009) used a modified form of the Avrami equation to represent the intrinsic healing or strength gain across a wetted crack interface over time:

$$R_h(t) = R_o + (1 - R_o)(1 - e^{-qt^r}) \quad (3)$$

In Equation 3, R_o represents the instantaneous fraction of strength gained, and q and r are material dependent parameters that are related to time dependent strength gain. They used a DSR to measure the intrinsic healing function of an asphalt binder over time and determine the parameters from Equation 3. By comparing the parameter R_o to the work of cohesion, they provided partial validation for the mechanism of intrinsic healing. They also speculated that since time dependent healing is driven by molecular motion, the rate of healing would increase with an increase in temperature. The following section presents a description of this test procedure along with some improvements.

3.1.3 Materials and test conditions

Three different asphalt binders were used in this study with performance grades of PG 64-22, PG 70-22, and PG 76-22. The asphalt binders were subjected to short-term aging using the rolling thin film oven (RTFO) following the procedure outlined in AASHTO T240 and long-term aging using the pressure aging vessel (PAV) following the procedure outlined in AASHTO R28.

Intrinsic healing for these binders was measured at three different temperatures. The temperatures were selected based on the PG grade and aging condition of the asphalt binder. At least three replicate measurements were made to determine the rate of intrinsic healing.

3.1.4 Experimental procedure to quantify intrinsic healing

Qiu and Bousmina (1999) used a DSR with multiple layers of polymers to determine the rate of inter-diffusion of molecules between the different polymers. Lamnawar and Maazouz (2006) used a similar approach to determine the rate of interaction between two polymer surfaces in contact with each other. Karlsson et al. (2007) used the DSR with an aged and an unaged binder specimen to determine the rate of inter-diffusion across the interface of the unaged and the aged asphalt binder. Subsequently, Bommavaram et al. (2009) used a DSR with two disc shaped binder specimens to determine the rate of intrinsic healing of asphalt binders. A slightly modified version of this test procedure was used for this study. In summary, the surfaces of two binder specimens are brought into contact with each other and the change in the shear modulus is recorded by applying a few small strain cyclic loads at different time intervals. By bringing the two surfaces into instantaneous and intimate contact with each other, the rate of wetting in Equation 1 is reduced to a dirac-delta function and the overall healing $R(t)$ reduces to the intrinsic healing $R_h(t)$. The change in the shear modulus over time for the two-piece specimen is normalized with respect to the single intact specimen of equivalent size to eliminate artifacts such as an increase in stiffness due to steric hardening. A description of the test procedure that was used for this study is presented below.

Two different types of disc shaped specimens were fabricated to determine the intrinsic healing function using the DSR. The first variant, referred to as the two-piece specimen, consisted of two binder specimens, each 40 mm in diameter and 3.5 mm in height. The second variant, referred to as the single piece specimen, consisted of a single binder specimen 40 mm in diameter and 7 mm in height. The specimens were fabricated by heating the binder to a temperature of 140 °C in an oven and pouring into aluminum molds with silicone lining. The aluminum mold with silicone lining has an inner diameter of 40 mm and a height of 3.5 mm and is mounted on a 1 mm thick leveled and smooth silicone base plate. A specially fabricated sharp blade was used to trim the specimen from the top to achieve the desired height of 3.5 mm or 7 mm as shown in Figure 3. The blade served as a template to reduce variability in specimen height and ensure a uniform surface. Use of the silicone lined aluminum mold with a leveled silicone base plate and the trimming blade ensured consistent and repeatable specimen geometry with a smooth surface for the test specimens. The liquid asphalt binder was allowed to gradually cool and solidify in the mold at room temperatures. Three single piece specimens and three pairs of the two-piece specimen were prepared using this procedure for each asphalt binder, temperature, and aging condition.

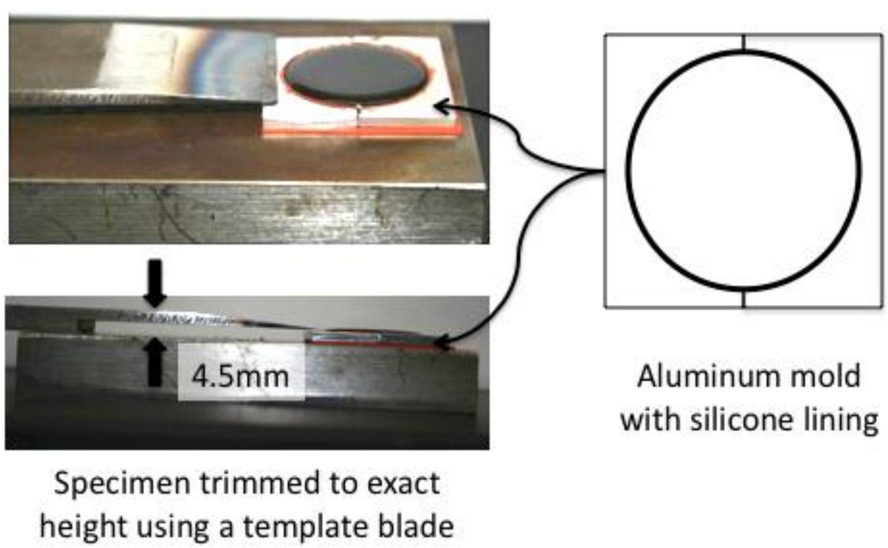

Figure 3: The silicon lined aluminum mold and trimmer used to fabricate the DSR test specimen

The DSR (model AR 2000) manufactured by TA Instruments, USA, was used in this study. The normal force and gap in the DSR was zeroed for a 40 mm parallel plate geometry before attaching the test specimens. The loading axis of the DSR was then raised to gain access to the bottom and top plates. The aluminum mold (with silicone lining) containing the trimmed specimen along with a base silicone sheet (1 mm thick) was placed on the bottom plate of the DSR. The top plate (which was heated using a flame gun) was gently lowered on to the top surface of the specimen with the help of the DSR's loading spindle. After allowing the specimen to bond with the top plate, the top plate with the specimen affixed to it was carefully extracted and allowed to stand at room temperature for about one hour. For the two-piece specimen, two 3.5 mm thick asphalt binder specimens attached with end plates were mounted on the top and bottom spindles. The specimens were then conditioned for around 30 minutes at the desired test temperature. After conditioning, the loading axis of the DSR with one of the two specimens was lowered at a rate of around 200 micrometers per second onto the lower plate with a termination trigger that was activated when the net normal force equaled 0.01 N. The slower (than previously used by Bommavaram, 2009) rate of loading also provides the equipment with a better control of normal force that helps achieve the desired normal force quickly. Lowering of the loading axis was followed by a 15 second equalization time that is required by the equipment to exert a steady force of 0.4 ±0.05 N on the specimen. The aforementioned sequence of steps was carried out to ensure complete wetting between the two faces of the two asphalt binder specimens at the desired test temperature. The exact same procedure was followed using the single piece specimen.

Following this initial setup, the DSR was programmed to measure and record the dynamic shear modulus (G*) at 0, 2, 4, 6, 8, 10, 15, 20, 25, 30, 40, 50 and 60 minutes of rest period counted from the time of establishing contact between two surfaces of the two-piece asphalt binder specimen. The G* was measured by applying sinusoidal loading with a strain amplitude of 0.01 % at a frequency of 10 radians per second for a duration of 20 seconds. The same procedure was repeated using a single piece asphalt binder specimen. The percentage of healing at any given time was computed as the ratio of the value of G* obtained using the two-piece specimen test to the value of G* obtained using the single-piece specimen. This normalization eliminates the effect of artifacts on the measured value of G* such as steric hardening or creep due to the small normal force applied during the test. A schematic of the actual steps to measure intrinsic healing is presented in Figure 4

In previous studies, approximately two minutes elapsed between the time the two specimens were brought into contact with each other and test was initiated. This delay cannot be completely eliminated, but it was minimized to 15 seconds by using the “squeeze/pull” test option available with the DSR to achieve the target normal force for the test procedure. This allowed a more accurate representation of the intrinsic healing process even for softer asphalt binders at higher temperatures.

One advantage of using this test procedure is that it allows the measurement of intrinsic healing of asphalt binders, which is different from the overall healing of the asphalt binder. Overall healing in asphalt binder or asphalt composites is typically measured by inducing damage to an intact specimen followed by measuring the rate of strength or stiffness gained over time. Consequently, the measured rate of overall healing is dependent on test conditions such as mode and magnitude of the damage induced prior to measurement of intrinsic healing. By isolating and determining the rate of intrinsic healing in asphalt binders it is possible to quantify and compare the inherent healing capacity of different asphalt binders. Results from the tests conducted using this procedure on three different asphalt binders at two different aging and three different temperature conditions are presented in Chapter 4.

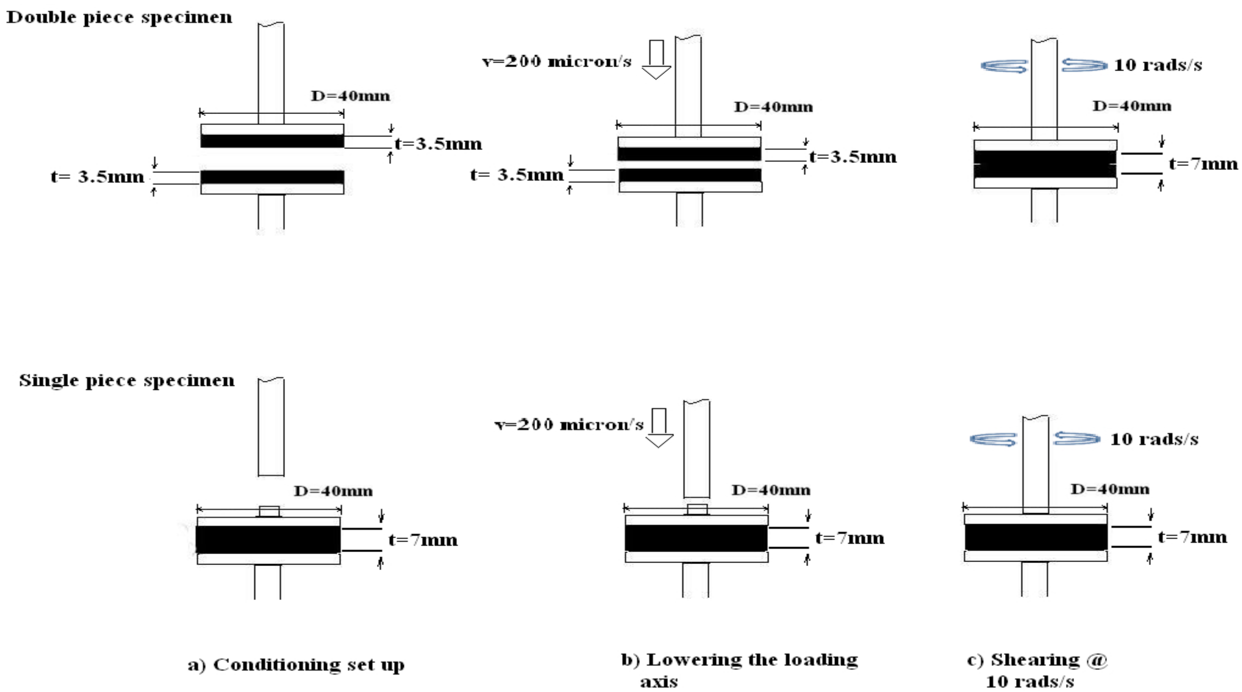

Figure 4: Schematic of steps to measure G* over time for the two-piece and single piece specimen

3.2 Quantifying overall healing using Viscoelastic Continuum Damage (VECD) Theory

The work potential theory is a continuum damage theory that describes the mechanical behavior of elastic material experiencing incremental damage using a damage evolution law derived from the principles of thermodynamics. The work potential theory relates the rate of growth of damage and the extent of damage to the change reflected in stress-strain behavior due to damage and develops a constitutive response model of damage specific to a material. Work potential theory is extended to viscoelastic materials by using the correspondence principles and modified damage evolution law. Elastic work potential theory is first described here before it is extended to model damage growth and healing in viscoelastic materials.

3.2.1 Damage evolution in elastic materials

Mechanical behavior of an elastic material with growing damage can be represented in terms of thermodynamic state variables. A thermodynamic state variable is a quantity that describes a specific thermodynamic system. In other words a set of thermodynamic state variables can uniquely define a state and are the control variables that are specified to reproduce that particular state of the system. Mechanical work physically deforms a material giving rise to a strain energy potential field. However, literature and experimental evidence clearly illustrate that the total mechanical work provided to the system is not completely utilized to develop strains as some of it also used to change the internal state variables (ISV) of that particular system. Accounting for this division in total work, the mathematical representation of strain energy is:

$$\partial W = \sigma \partial \epsilon \tag{4}$$

Emphasis is placed on the partial differential representation as opposed to complete differential as the total work W = W (ϵ,S) is a function of both the strain and the internal state variable.

Schapery (1990) developed a theory describing the mechanical behavior of materials that exhibit path independence in measured work. The growth in damage is attributed to the change in the ISV's and thermodynamic theories are applied to describe this change as a function of input loading. The generalized theory attributes ISV's to a variety of failure phenomena such as micro-growth and macro crack growth. A brief introduction to the development and laws of the damage evolution theory is as follows.

The fundamental aim of the work potential theory is to quantify total work (W_T) spent on a material with changing ISV's purely as a function of stress and strains. Consider a process in which the input load not only deforms a material but also changes its state variables with time. In this case the total work is defined as the area under the stress-strain curve. The idea behind the goal of quantifying total work as a function of strains alone would be to use the hyper-elastic model to characterize the stress–strain behavior especially if the change in ISV's is used to describe damage evolution. The starting point of the work potential theory is to assume path independence for measured work. In other words, a unique strain energy potential derived as a function of ISV's and strain can be associated with the material. Uniqueness in strain energy potential here refers to the fact that there exists a unique value of energy which is required to change a given set of ISV's and strain to another. Also it is reasonable to assume that a material that exhibits uniqueness in strain energy potential, will also exhibit a unique stress potential as a function of ISV's and strains. Currently only one ISV will be used as an aid to illustrate the concepts as a similar formulation can be extended to multiple ISV's without any additional assumptions. More specifically, this single internal state variable is used to represent a lump sum change in the material due to micro damage. From here on, a positive change in the ISV or evolution of damage are used interchangeably as they both refer to change in the thermodynamic state of the material that corresponds to damage.

Figure 5 represents a 3-D plot of the stress value as a function of strain and a hypothetical ISV denoted by 'S'. This plot can be developed by measuring the strain response while 'S' is constant and applying different stress levels. It is hypothesized in this research that in an actual process the W (deformation energy at constant S) at any damaged state can be measured by plotting the stress-strain behavior while unloading the material from that damaged state. Unloading process is chosen over the loading process as during unloading it is unlikely for a material to experience damage or change in the state variable related to damage. The work W1 (or W2) as shown in

Figure 5 is assumed to be the work needed (area under stress-strain curve) by the material to reach point 1 (or 2) from zero strain level to $\epsilon 1$ (or $\epsilon 2$) while maintaining S1 (or S2) constant.

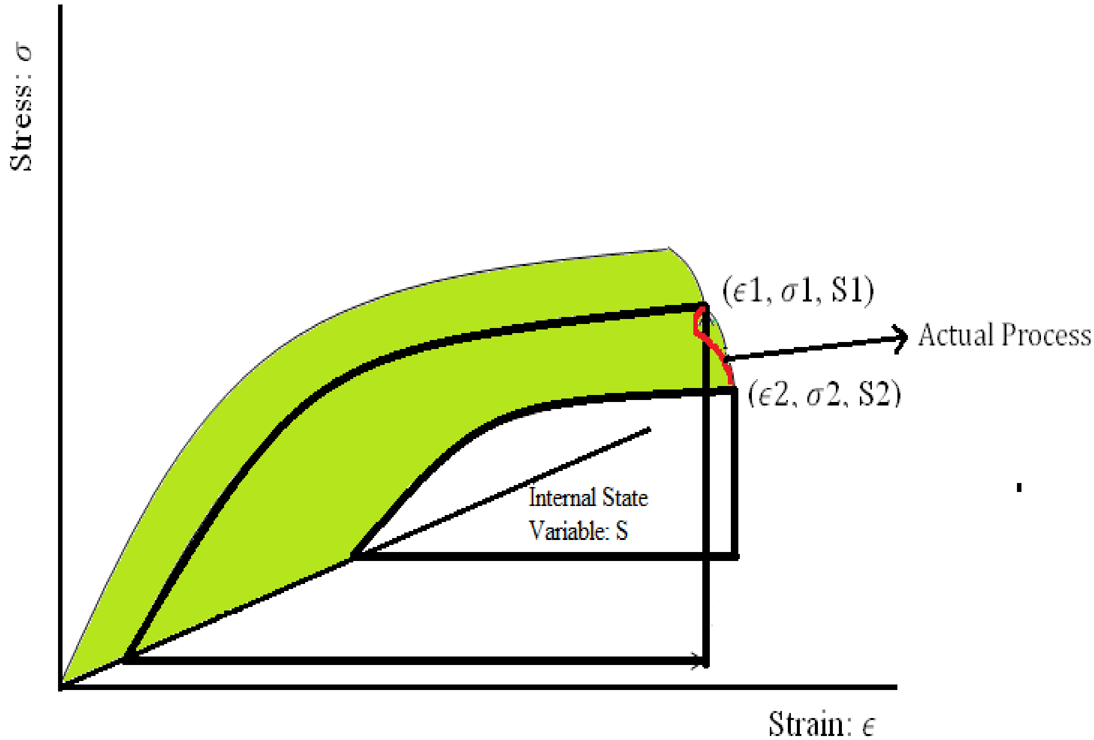

Figure 5: Hypothesized stress-strain and state variable plot

A mechanical process that changes the material state from ($\epsilon 1$, S1, $\sigma 1$) to ($\epsilon 2$, S2, $\sigma 2$) is represented by the red line curve in Figure 5. The total work (W_T) associated with such a process is calculated using the integral form of Equation 4. W_T can be graphically interpreted as the area under the stress-strain curve obtained by collapsing the 3-D potential plot (Figure 5) to a conventional stress-strain plot as shown in Figure 6 . A relationship can be established between W1, W2 and the total work based on the principles of conservation of energy. The difference in W2 and W1 as represented in Figure 6 (unshaded area) can be partially accounted by the area under the curve representing an actual process as shown in Figure 7 and with the remainder represented by some assumed quantity W_s. Based on Figures 5, 6 and 7 it can be inferred that the quantity W_s will drop to zero provided a material is subjected to a mechanical process that will only deform the material and not cause the ISV to change. Thus an interpretation of the quantity W_s can be the work required to change the state with respect to the ISV representative of damage. In conclusion it can be said that the total work (W_T) supplied in an actual process is mathematically equal to the sum of pure deformation energy W and energy W_s corresponding to change in state or structure. This is represented as:

$$W_T = W + W_s \tag{5}$$

Where $W_T = \int \sigma d\epsilon$

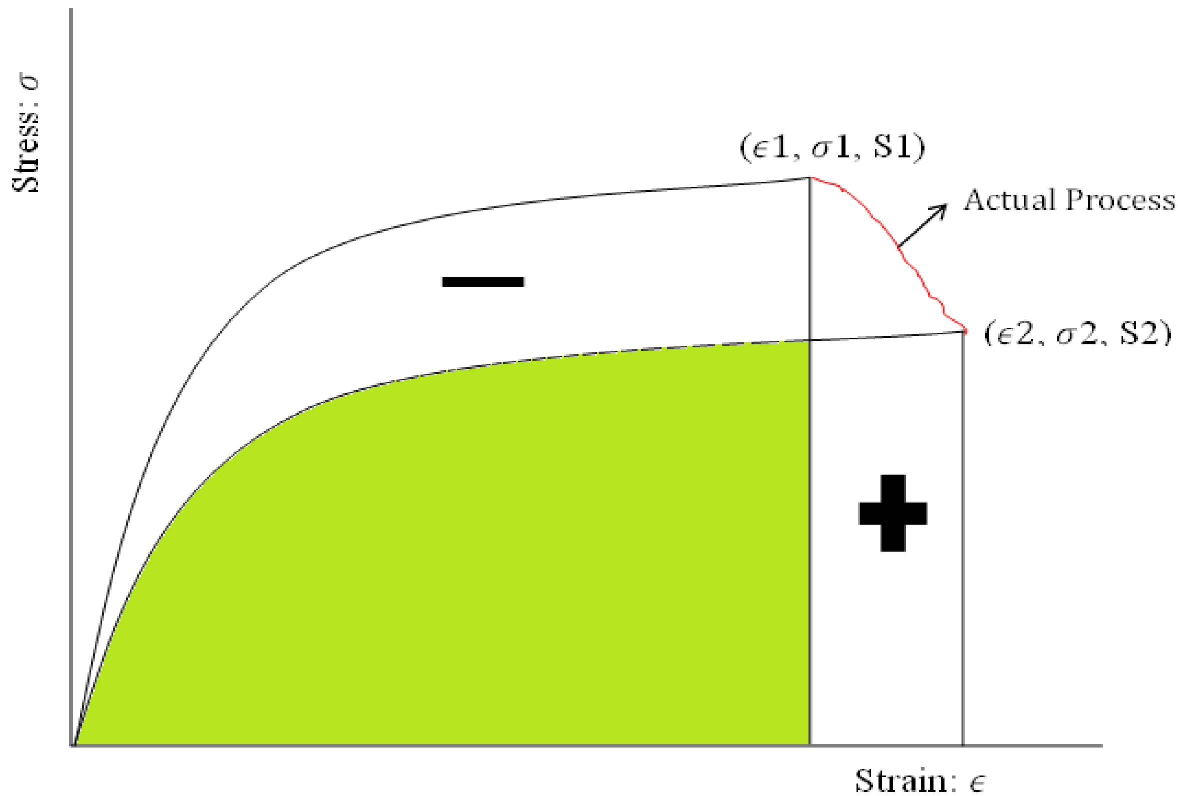

Figure 6: Two dimensional representation of the actual process

Note: The area under the curve with point ($\epsilon 1$, $\sigma 1$, S1) is equal to W1 and W2 corresponds to ($\epsilon 2$, $\sigma 2$, S2). The sum of positive and the negative area (represented in plot) is equal to difference in W1 and W2.

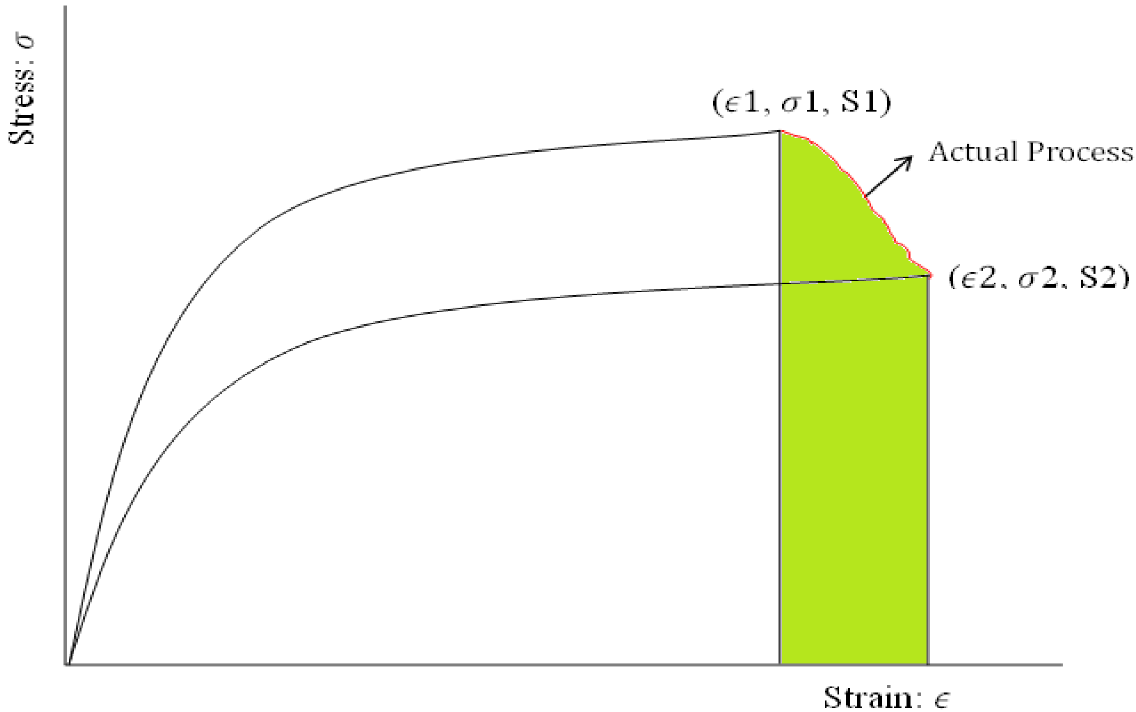

Figure 7: Area under the Actual process

Based on Equation 5 and keeping in view the requirement of a hyper-elastic constitutive model, Schapery (1990) proposed an "evolution law" that relates W_T with S and elastic strain energy to the given strains. According to this evolution law the rate of change of pure deformation work W with respect to S should be equal to the rate of change of damage energy W_s with respect to S provided the condition that $\frac{dS}{dt}$ not equals zero is satisfied. Mathematically this can be represented as:

$$\frac{\partial W}{\partial S} = -\frac{\partial W_s}{\partial S} \tag{6}$$

Park et al. (1996) interpreted the left hand side of Equation 6 as the available thermodynamic force for growth of damage and the right hand side the required force. The proof behind the rate evolution theory as given by Schapery is as follows.

An infinitesimal change in work done in a quasi-static process with a constant ISV (with respect to time) can be represented as:

$$dW = \frac{\partial W}{\partial \epsilon} d\epsilon + \frac{\partial W}{\partial S} dS \tag{7}$$

Where from Equation 4 and from the definition of thermodynamic force (f_m) as a negative rate of change of work with respect ISV we get:

$$dW = \sigma d\epsilon - f_m dS \tag{8}$$

Where$f_m = -\frac{\partial W}{\partial S}$.

From the above equation and definition of total work in an actual process ($\frac{dS}{dt}$ ~= 0) we get:

$$dW = dW_T - f_m dS \tag{9}$$

This on integration and rearrangement yields:

$$W_T = W + \int f_m dS \tag{10}$$

Finally by comparing Equation 5 and 10 we get the evolution law as:

$$f_m = -\frac{\partial W_s}{\partial S} \tag{11}$$

Thus with the set of data for W_T from experimental tests and assuming certain quantities as representative of ISV's, the evolution law (Equation 11 or 6) can be used to arrive at the unique strain energy potential as a property characteristic of a specific material. Eventually this unique potential along with damage energy can be used to predict any stress level given a loading history for that specific material.

The utility of this damage evolution law as used in many earlier works such as Schapery (1987, 1989), Park et al.(1994, 1996) to name a few, is demonstrated below in an experimental setting to improve the clarity and provide a general framework which will aid in the extension of philosophies to viscoelastic materials:

1. *Selecting ISV's*: The first step in formulating a constitutive model is to select an ISV which will aptly represent the damage process in the material. For example, temperature of the material can be taken as an ISV while modeling soils or organic polymers as the strain energy significantly varies with temperature. Schapery (1987) choose the ISV S as W_s itself while modeling an elastic bar in axial tension. W_s represents the dissipated work due to evolution of damage and the level of damage or change in structure can be gauged by its magnitude, making it a good contender to act as an ISV. Also for the uniaxial loading chosen by Schapery (1987) axisymmetric damage starts to accumulate turning the isotropic material into a transversely isotropic material with progression of damage, as the damage manifestation is evident only in the change in stiffness in one particular direction, only one ISV, W_s, was chosen to represent the evolution of damage. Similar such assumptions can be made for different processes to identify (pinpoint) the ISV's needed to best describe the damage in a process.
2. *Assuming strain energy potential*: Strain energy potential as mentioned earlier is a unique material characteristic. One way to identify the potential function dependent on both S and strains is to consider a general stress-strain behavior with and without damage and fit a function to the data. Functions of S or damage level can then be introduced into

parameters present in the functional form used to fit the stress-strain data to obtain a multidimensional stress potential from which using Equation 4 we can obtain unique strain energy potential. Another way to identify the strain energy potential would be to build on the prior knowledge of stress vs. strain curves obtained using principle of classic fracture mechanics. Park et al. (1996) and Lee et al. (1998) chose the first method and arrived at the constitutive relationship by observing stress vs. strain (or pseudo strain in this case) behavior by performing numerous fatigue tests. The study successfully demonstrated that using such an approach to characterize fatigue damage in asphalt mixes is both feasible and comparatively very accurate. Schapery (1987) chose the second approach and obtained the stress-strain relationship by employing the equation for transversely isotropic linear material. In the functional forms obtained the moduli were replaced by functions of S so to incorporate the effect of growing damage. Usually the level of complexities would increase if the tensorial nature of stress-strain measurements is considered, however in this research simple monotonic or cyclic shear tests were performed with emphasis placed only the overall shear response.

3. *Evolution law*: Before using the evolution law to relate the parameter S with the strain history, it is important to identify the quantity W_s as a function of S. Given the value of W_s and the ISV S, regression analysis would be one way of empirically formulating $W_s(s)$. For a simple case of proportional loading and single ISV, the value of W_s can be measured by subtracting the work done (W at constant S) while unloading, from the total work supplied to a material while deforming it. Other procedures to formulate $W_s(s)$ would be either by observation or by theoretical analysis of damage energy using principles of fracture mechanics. Given $W_s(s)$, the data of W_T from

material tests and the assumed form of W(ϵ, S) (step 2) , the evolution law can be used to relate S from $W_s(s)$ and ϵ from W(ϵ, S) . This relationship now can be utilized to arrive at the assumed parameters used in the functional form of W (ϵ, S) concluding the process of formulating the unique strain energy potential for the material. The reader is referred to works done by Schapery (1987) on damage modeling of solid rocket propellant to get a mathematical understanding of the process explained above.

Finally, with the functional form of quantities W and damage energy (W_S) and the relationship between ISV "S" and strains obtained through the evolution law, the total required work (W_T) can be calculated using Equation 5 as a function of strains alone. Stress values can be predicted using this functional form of W_T which is based on a unique form of W, given any strain history.

3.2.2 Damage evolution in Viscoelastic materials

Schapery (1990) also demonstrated that the work potential theory or elastic continuum damage theory could be successfully extended to describe damage evolution in viscoelastic materials by using the correspondence principles and a new damage evolution law. Kim and co-workers (1996, 1998, and 2002) used a similar approach and provided significant evidence to demonstrate that the viscoelastic continuum damage theory (VECD) can be used to characterize fatigue damage in an asphalt concrete mix independent of the specific mode of loading or test conditions. The two main components of this approach are (i) the correspondence principles that transform the material stress-strain state into a pseudo domain where the material exhibits a linear elastic stress-strain behavior and (ii) the damage evolution law that relates the pseudo stress-pseudo strain to any change in S.

3.2.2.1 Correspondence principles

A challenge with viscoelastic materials compared to elastic materials is that the solution to boundary value problems involving a viscoelastic material requires that the constitutive equations include time, which is not the case for elastic materials. An additional challenge with characterizing the healing response of viscoelastic materials is that under certain loading conditions, the time dependent response of a material and the healing response have a similar manifestation. In other words, the confounding behavior of viscoelastic recovery or relaxation is hard to separate out from the time dependent occurrence of healing, as both the phenomena have positive influential effects on material stiffness. A simple example explaining the apparent similarity of healing and viscoelastic response is as follows. Under the application of a uniaxial stress, a viscoelastic material usually responds with an instantaneous deformation followed by a time dependent deformation. Upon unloading or providing a rest period before the onset of damage, the material reverses the deformation either fully or partially resulting in a reduced compliance (or stiffening) at a given time. If this scenario were repeated after the introduction of micro-damage followed by healing during the rest period, the overall mechanical response of the material would be the same as before, i.e., a reduction in compliance or gain in stiffness (ratio of stress and strain) after the rest period. However, this entire gain in stiffness cannot be attributed solely to healing as it fails to account for the natural viscoelastic recovery that results in an increase in stiffness if measured immediately after the rest period. This can artificially over estimate the amount of healing that actually occurs in the sample. This example also highlights the need to account for the time dependent behavior of the material. This section will first address the mathematical tools by which boundary value problems for time dependent materials can be solved using an analogous solution for an elastic material.

Earlier attempts to simplify viscoelastic boundary problems involved the use of integral or Laplace transformations. The idea was to apply Laplace transforms to transform the viscoelastic boundary value problem into a corresponding elastic problem. In this transformed space, the problem is treated as a boundary value problem for an elastic material enabling the user to apply known elastic solutions and obtain the necessary stress-strain and displacement fields. However a major drawback to such an approach is that it can only be applied to problems with a constant traction boundary surface, which is clearly not the case when the material experiences damage. Also inverse transformation of the solution from the Laplace/ Fourier spaces to the original time space are prone to mathematical errors or are sometimes unsolvable. To account for viscoelastic recovery and other viscoelastic responses with growing damage (change in traction surface) without the involvement of complexities arising due to inverse transformations, Schapery (1984) introduced the concept of modified correspondence principles. The modified correspondence principles transform the viscoelastic response to a mathematically equivalent elastic response by using hereditary integral representation of viscoelastic stress-strain relations. A new set of quantities such as pseudo stress and pseudo strains (in the transformed domain) are formulated and used in the equilibrium and compatibility equations to develop the boundary value solution.

Understanding the behavior of time dependent material is necessary to develop the concept of pseudo variables. Theory of linear viscoelasticity has been successful in predicting the time dependent response of materials such as asphalt concrete. A material is assumed to behave as linear viscoelastic material if it follows the following two principles of superposition:

1. F($K_1 x$)= K_1*F(x)
2. F($K_1 x + K_2 x$) = K_1F(x)+K_2F(x)

Following these superposition principles the viscoelastic stress – strain response can be related using the Boltzmann superposition integral also known as convolution or hereditary integral:

$$\sigma = \int_0^t E(t-\tau) * \frac{d\epsilon}{d\tau} d\tau \tag{12}$$

Where σ= stress as function of time

ϵ = strain as function of time

$E(t)$ = Relaxation modulus of the material.

An inverse form of which is:

$$\epsilon = \int_0^t D(t-\tau) * \frac{d\sigma}{d\tau} d\tau \tag{13}$$

Where *D (t)* represents the viscoelastic creep compliance of the material

Schapery (1981, 1984) introduced pseudo variables which in a rudimentary sense are similar to either the stress or the strain response calculated using the hereditary integral (Equations 12 or 13). The idea behind such formulation is simple yet powerful and follows the argument that the relationship between the pseudo variables (where one of the two variables is transformed using Equations 12 or 13 and the other is as is) will always yield a straight line similar to that of linear elastic behavior provided that the material follows the linear viscoelastic theory. Such a stress-pseudo strain behavior (or pseudo stress-strain behavior) is analogous to the stress-strain behavior of an elastic material and is mathematically represented as follows:

$$\sigma^R = E_R \epsilon^R \ or \ \epsilon^R = \frac{\sigma^R}{E_R} \tag{14}$$

Where $\epsilon^R is\ defined\ as$ $\epsilon^R = \frac{1}{E_R}\int_0^t E(t-\tau) * \frac{d\epsilon}{d\tau} d\tau$. Here E_R is referred to as reference modulus and is dimensionally equal to the relaxation modulus and ϵ^R the pseudo strain. Similarly the pseudo stress is formulated using a substitution analogous to Equation 13 depending on the type of correspondence principle used. Schapery (1984) proposed that such a formulation is not only valid for linear viscoelastic material but also for nonlinear viscoelastic material, provided that the relaxation modulus representative of a nonlinear material behavior is substituted in Equation 14.

Using the concept of pseudo variables avoids incorporating time dependency while solving a boundary value problem. However, additional proofs are required to demonstrate the applicability of such pseudo quantities in equilibrium and compatibility equations. Schapery (1981) introduced three different correspondence principles with elaborate proofs demonstrating the use of these pseudo variables to solve viscoelastic boundary value problem using solutions applicable for an elastic material. In this research CP-II or correspondence principle II is used to address the history dependent effects. CP-II briefly states that the viscoelastic problem with a rate dependent increase in surface boundary can be reduced to an equivalent elastic problem by using physical stresses and pseudo strains. Mathematically it can be represented as:

- The pseudo stress σ^R=σ; where σ is the time dependent stress developed or applied to a viscoelastic material.
- Pseudo strain ϵ^R=$\frac{1}{E_R}\int_0^t E(t-\tau) * \frac{d\epsilon}{d\tau} d\tau$; where ϵ is the time dependent strain developed or applied to a viscoelastic material.
- And pseudo strain energy an analog of strain energy in pseudo domain; $W^R = W(\epsilon^R, S)$ where S denotes the internal state variable.

Experimental validation of correspondence principle II can be found documented in research works done by Lee et al. (1995, 1998) and Park et al. (1994, 1996).

3.2.2.2 Damage evolution law for viscoelastic materials

Correspondence principles translate the stresses and strains into pseudo domain where the analogous pseudo stress and pseudo strain exhibit an elastic relationship. These pseudo variables can now be used to replace the stresses and strains appearing in elastic constitutive equations and the pseudo strain energy an analog of strain energy can now represent the energy potential to be used in work potential theory. However the damage evolution law cannot be directly applied as the damage growth in viscoelastic material exhibits additional rate dependence which is not completely accounted for through ϵ^R alone. To account for this additional rate dependence Schapery (1975, 1984) proposed a new evolution (equation (15)),

$$\dot{S} = \left(-\frac{\partial W^R}{\partial S}\right)^{\alpha_m} \tag{15}$$

Where α_m is a material constant and $\dot{S}$ represents the time derivative of ISV S.

Schapery (1981) proposed that the rate at which a crack propagates unhindered in a material is proportional to a function of J integral. J integral can be interpreted as the work available to inflict damage and it was demonstrated to be proportional to the applied stress raised to a material parameter m or:

$$\frac{dS}{dt} = f(J^R) \tag{16}$$

Where: J^R is the J integral value calculated for viscoelastic materials in pseudo domain and 'S' is the ISV. Similar to J integral the J^R value is also proportional to the input stress:

$$J^R \sim (\sigma^R)^m \tag{17}$$

Where: m is a material function, which was later related to the linear viscoelastic creep compliance of the material. Thus from (17) and (16) we get:

$$\frac{dS}{dt} = f_1((\sigma^R)^m) \tag{18}$$

Equation 18 also sometimes referred to as the power law of crack growth, was then used to relate the rate of change of internal state variable S with the amount of energy associated with the change in S. The math behind the derivation is not presented in this study as it requires additional background on crack initiation and crack growth mechanisms. Eventually from various physical and mathematical considerations governing crack growth, a damage evolution law which retained the essential features of elastic work potential theory emerged from Equation 18 in the form as presented in Equation 15. The evolution law was demonstrated to be successful in relating S with pseudo strains in many works done by Schapery (1975, 1981, 1984), Park et al. (1996, 1994) and Kim and Lee et al. (1998). A limitation to this evolution law is that it doesn't take into account the plastic deformation, which however is not the focus of this study.

Using this modified form of evolution law and correspondence principles, the three steps previously mentioned in Section 3.2.1 can be applied for viscoelastic materials to develop a characteristic damage property: C(S), where C is the pseudo stiffness and S the damage parameter, which similar to strain energy potential is unique for a given viscoelastic material. More details of the function C(S) will be presented below in Section 3.2.3.2

3.2.3 Experimental and analytical method to quantify damage and healing in FAM mixes

3.2.3.1 Materials and test conditions

This study was conducted using FAM mixes subjected to cyclic loading in torsion using a Dynamic Shear Rheometer (DSR) (AR 2000 manufactured by TA instruments). Fatigue in FAM specimen is chosen over regular asphalt specimen as damage evolution and consequently healing is generally concentrated in this fraction of a regular asphalt mix. However, it must be noted that although this study was conducted on FAM mixes, the analytical and experimental procedures can be applied to investigate the healing characteristics of full asphalt mixtures. Four different FAM mixes manufactured using one type of aggregate, two different types of asphalt binders and two different binder contents were used in this study. The aggregate used in the FAM specimens was a limestone from Bryan, TX, passing ASTM sieve no 16. The gradation of the fine aggregates in the FAM mix was similar to the gradation of the fine aggregate portion of a typical dense graded asphalt mix. The four FAM mixes were designated as 10-64-16, 12-64-16, 10-67-22 and 12-67-22. The first number in the designation represents the percentage of binder by weight of the mix and the second two numbers (separated by a hyphen) denote the PG grade of the binder used. The tests were performed on cylindrical FAM specimens that were 20 mm in diameter and 50 mm in height. These specimens were cored from a bigger 100 mm diameter and 75 mm high specimen compacted using the Super-pave gyratory compactor. The cylindrical FAM test specimens were glued to end plates and used with the DSR for testing. All tests in this study were conducted at a temperature of 25 °C.

3.2.3.2 Validating the use of VECD theory to characterize damage in FAM specimens

Previous studies successfully used the VECD theory to develop a material function denoted by C(*S*) that relates the pseudo stiffness *C* of the material to an internal state variable *S* that reflects damage. This function represents the evolution of fatigue damage in asphalt mixtures and similar to proposition of strain energy potential is unique for a given viscoelastic material. Most of these studies were conducted on full asphalt mixtures subjected to a cyclic tension or tension-compression mode. To the best of the authors' knowledge, this theory has not been applied to FAM specimens subjected to cyclic torsion. Therefore, the first task of this study was to obtain the characteristic damage function for the FAM mixes and more importantly to verify that this function was a material property independent of the mode of testing.

The following protocol was used to characterize fatigue damage using the DSR. The FAM specimen was first subjected to a creep load of 1 kPa for one minute followed by a recovery period of 15 minutes. The creep-recovery was followed by application of cyclic loads following a sinusoidal waveform with stress amplitude of 1 kPa at 10 Hz. These two tests were conducted to measure the linear viscoelastic properties of the specimen. Although the response of the specimen to cyclic loads can be computed mathematically using the creep compliance data, the cyclic test was conducted to provide redundancy and verify the linear viscoelastic properties of the specimen. The test specimen was then subjected to a cyclic load following a sinusoidal waveform with stress amplitude of 220 kPa at 10 Hz to induce fatigue damage. At least 2 replicate samples were tested to obtain the fatigue cracking characteristics for each type of mix. In addition, three specimens of mix 12-67-22 were subjected to monotonic loads at 22 kPa per minute and cyclic loads with a strain amplitude of 0.6% and stress amplitude of 200 kPa at 10 Hz. Two specimens of mix 10-67-22 were subjected to cyclic loads with strain amplitude of 0.6% and 0.8% at 10 Hz. These additional tests were conducted to verify the applicability of the VECD theory to FAM specimens subjected to torsional loading.

Correspondence principles (CP-II) were first used to transform the time dependent stress-strain data into a pseudo domain that corresponds to a hypothetical elastic material. Given the transformed data, a procedure similar to the three steps followed to characterize damage in elastic materials as mentioned in Section 3.2.1, is used in this study to characterize damage evolution in viscoelastic materials:

1. Selecting ISV's: Kim et al. (1998) and Park et al. (1996, 1998) conducted a series of monotonic and cyclic loading tests in both controlled stress and strain modes on asphalt concrete and concluded that pseudo stiffness (C), defined as slope of $\square^{R}$-$\square^{R}$ σ^{R}-ϵ^{R} plot, suitably reflected the manifestation of damage in viscoelastic materials. Shear monotonic tests conducted on cylindrical FAM samples verified this conclusion. Figure 8 shows the plot between pseudo stress and pseudo strain for monotonic shear tests conducted at varying strain rates. To describe this rate dependent change in C, "damage parameter" S_p (henceforth represented as S) formulated by Schapery (1981) is used as the internal state variable. The damage parameter is formulated based on the characteristics of micro-crack growth in particulate viscoelastic material with multiple flaws. Since the purpose of this study is to characterize micro-crack growth and micro-crack healing, use of the damage parameter as the ISV is both practical and justified. The time dependent damage parameter is developed based on the generalization of micro-crack growth law and is mathematically represented as:

$$S_p = \left(\int_0^t |\epsilon^R|^p \, dt \right)^{1/p} \tag{19}$$

   Where K= (1+1/m) or 1/m dependent on the mode of failure. The parameter m is an exponent of the power law relationship of linear viscoelastic creep compliance with time.

2. Computing the strain energy potential: Based on the pseudo stress-pseudo strain behavior of asphalt concrete subjected to simple uniaxial cyclic fatigue tests, Lee and Kim (1998) proposed a simple constitutive model as follows:

$$\sigma^R = (F + G) * \epsilon^R * I \tag{20}$$

And the strain energy potential based on equation (20) is given as:

$$W^R = \frac{1}{2} * I(F + G) * (\epsilon^R)^2 \tag{21}$$

Where, the function F represents a factor that accommodates the change in pseudo stiffness, function G represents hysteretic behavior in the pseudo stress-pseudo strain relationship and I the initial pseudo stiffness was introduced to reduce specimen-to-specimen variability. A similar model can be adopted to characterize fatigue life in FAM mixes. In this study fatigue damage was characterized in terms of the loss in stiffness and the following forms of equations (20) and (21) used:

$$\sigma^R = C(S) * \epsilon^R \tag{22}$$

$$W^R = \frac{1}{2} * C(S) * (\epsilon^R)^2 \tag{23}$$

where, $C(S)$ represents the change in stiffness as a function of S, σ^R represents the pseudo stress and ϵ^R represents pseudo strain.

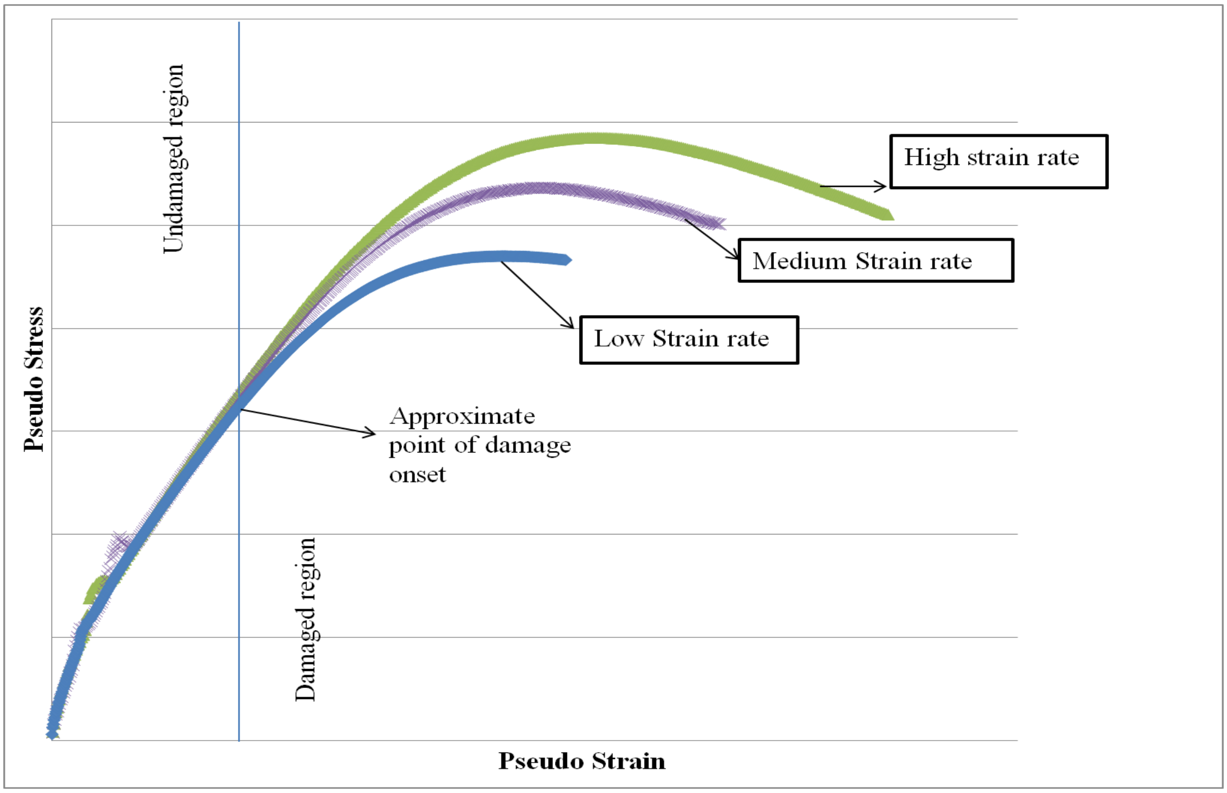

Figure 8: Plot between pseudo stress and pseudo strain for monotonic shear tests conducted at varying strain rates.

3. Damage evolution law: Schapery (1981) proposed a rate dependent damage evolution law, a variation of which was developed by Lee and Kim (1998) for asphalt mixtures. This simplified equation relating S, ϵ^R and C is given by :

$$S \cong \sum_{i=1}^{n}[0.5 * (\epsilon^{R}{}_{i})^2 * (C_{i-1} - C_i)]^{\frac{\alpha}{1+\alpha}} * (t_i - t_{i-1})^{\frac{1}{1+\alpha}} \tag{24}$$

In equation (24), α is related to the material creep and is suggested to take values of $\left(1+{}^{1}\!/_{m}\right)$ or ${}^{1}\!/_{m}$ depending on the type of fracture, where m is the exponent of linear viscoelastic creep compliance.

The above approach was used to obtain the characteristic damage evolution for the four different FAM mixes used in this study. As mentioned earlier, two of these four mixes were also subjected to different modes and amplitudes of loading to verify whether the *C(S)* was a characteristic material property. Specimens of the mix 12-67-22 were subjected to three different rates of monotonic loading and cyclic loading. Specimens of the mix 10-67-22 were subjected to cyclic loading with two different loading amplitudes. Figure 9 illustrates that the characteristic damage evolution curve obtained using Equation 24 was similar for each of the two mixes irrespective of the mode and amplitude of loading. The results in Figure 9 also support the suitability of using the VECD theory for FAM mixes subjected to torsional fatigue.

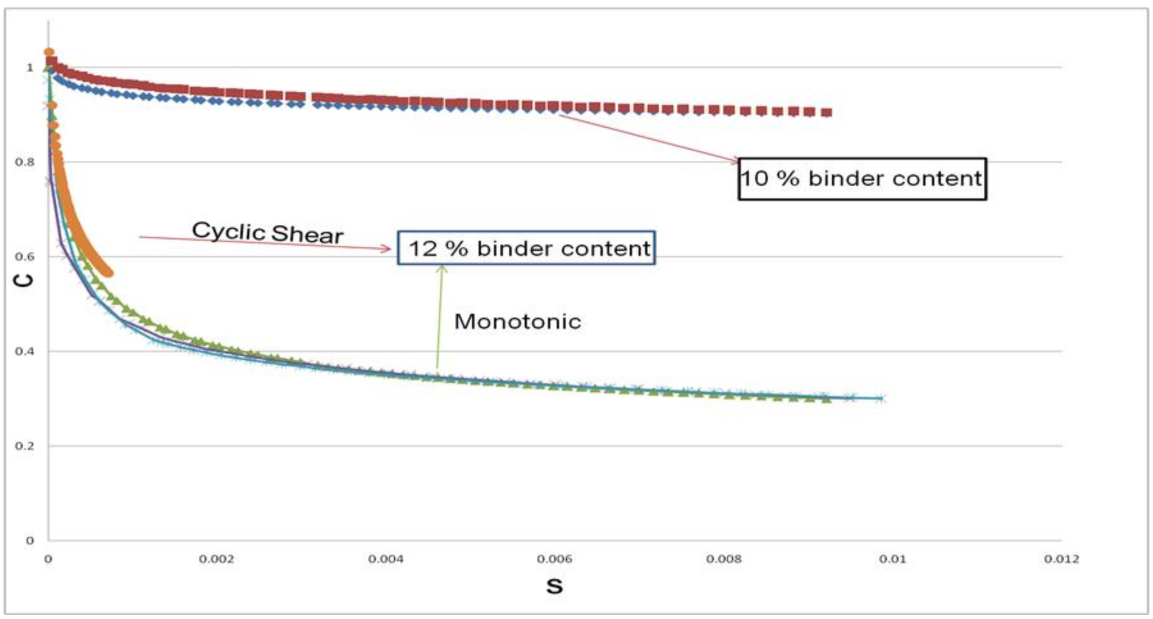

Figure 9: C vs. .S curves for two different FAM mixes, tested in different modes of loading

3.2.3.3 General methodology to quantify healing

According to the work potential theory, damage is defined as a process that results in an increment in the value of the internal state variable *S*. Healing, which is in essence the reversal of micro-damage, can therefore be defined as a process that produces a net reduction in value of the state variable *S*. As mentioned earlier, a change in the state of the material can be mapped to a unique set of values for S, ϵ and σ and the damage evolution law relates the stiffness based on the loading history to *S*. Therefore, healing can be quantified in terms of the reduction in the value of *S* and treated as a global material property.

In this study, the amount of healing is quantified as the relative percentage reduction in the damage parameter *S* and is mathematically defined as:

$$\%\ \text{Healing}(C, t) \equiv \frac{(S_{f} - S_{i})}{(S_{i})} * 100 \tag{25}$$

where, C represents the pseudo stiffness immediately before the rest period, t denotes the duration of the rest period, and $S_i(C)$ and $S_f(C, t)$ correspond to the internal state variables representing the state of material before and after the introduction of a rest period, respectively. Calculating the value of $S_i(C)$ is well established in the VECD theory and it requires the application of the damage evolution law for a given loading history. On the other hand, $S_f(C, t)$ is the result of a thermo-chemical healing process and cannot be calculated directly since it requires an evolution law that relates S_f to the unknown chemical and thermodynamic forces that drive healing. While the investigation and development of such a law is a subject of ongoing research it was beyond the scope of this study. Instead, it was hypothesized that $S_f(C, t)$ could be back calculated by applying additional load cycles to a test specimen immediately after the rest period.

An apparently straightforward way to obtain the value of $S_f(C,t)$ is to measure the pseudo stiffness C_f immediately after the rest period of duration t and use this with the *C(S)* function to determine $S_f(C,t)$ (see schematic in Figure 10). However, this method can only be used when the damage evolution in the partially healed specimen is the same as the damage evolution in the intact specimen. During the tests conducted in this study it was found that there is a marked deviation in the evolution of damage following the rest period as compared to the original specimen (Region-I in Figure 10). However, as the loading is continued the damage evolution in the post-healed specimen eventually is similar to the damage evolution in the intact specimen (Region-II in Figure 10).This is typically after the pseudo stiffness of the post-healed specimen reduces to less than the pseudo stiffness prior to the rest period. Lee and Kim (1998) and Little et al. (2001) reported similar differences in the damage evolution characteristics of the mix immediately after the rest period. They speculated that upon allowing a damaged material to heal, weak bonds are formed across the cracked interface that gains strength over time. The bonds that only gain partial strength are weaker and easier to break and thus contribute to a faster rate of damage evolution compared to the intact specimen. In conclusion, it can be stated that the stiffness immediately following the rest period may not be a good representation of the level of damage reversal in the matrix and therefore is not recommended to obtain the value of $S_f(C,t)$. Such a direct measurement of the pseudo stiffness, C_f and corresponding $S_f(C,t)$ is very likely to over predict healing and render the predictions to be dependent on the amplitude of loading.

In order to avoid the aforementioned shortcoming, an alternative method was used to estimate $S_f(C,t)$. In this method the pseudo stiffness used to determine $S_f(C,t)$ from the *C(S)* function is not the measured pseudo stiffness immediately after healing C_f but a *reduced pseudo* *stiffness,* $C_f^{'}$. This reduced pseudo stiffness represents the equivalent effect of both partially healed and fully healed bonds within the matrix after the rest period. The procedure used to obtain the reduced pseudo stiffness was as follows. Curves 1 and 2 in the schematic Figure 11 (denoted as C^{1} and C^{2}) represent the measured damage evolution in the intact specimen before and after partial healing, respectively. Curve 3 (denoted as C^{3}) was then developed using data from Region II such that it has the same functional form as Curve 1 (which is known apriori) and extrapolated backwards to predict the reduced pseudo stiffness $C_f^{'}$ and determine $S_f\left(C,t\right)$ using the $C\left(S\right)$ relationship. Finally, $\%H\left(C,t\right)$ was computed using Equation 25.

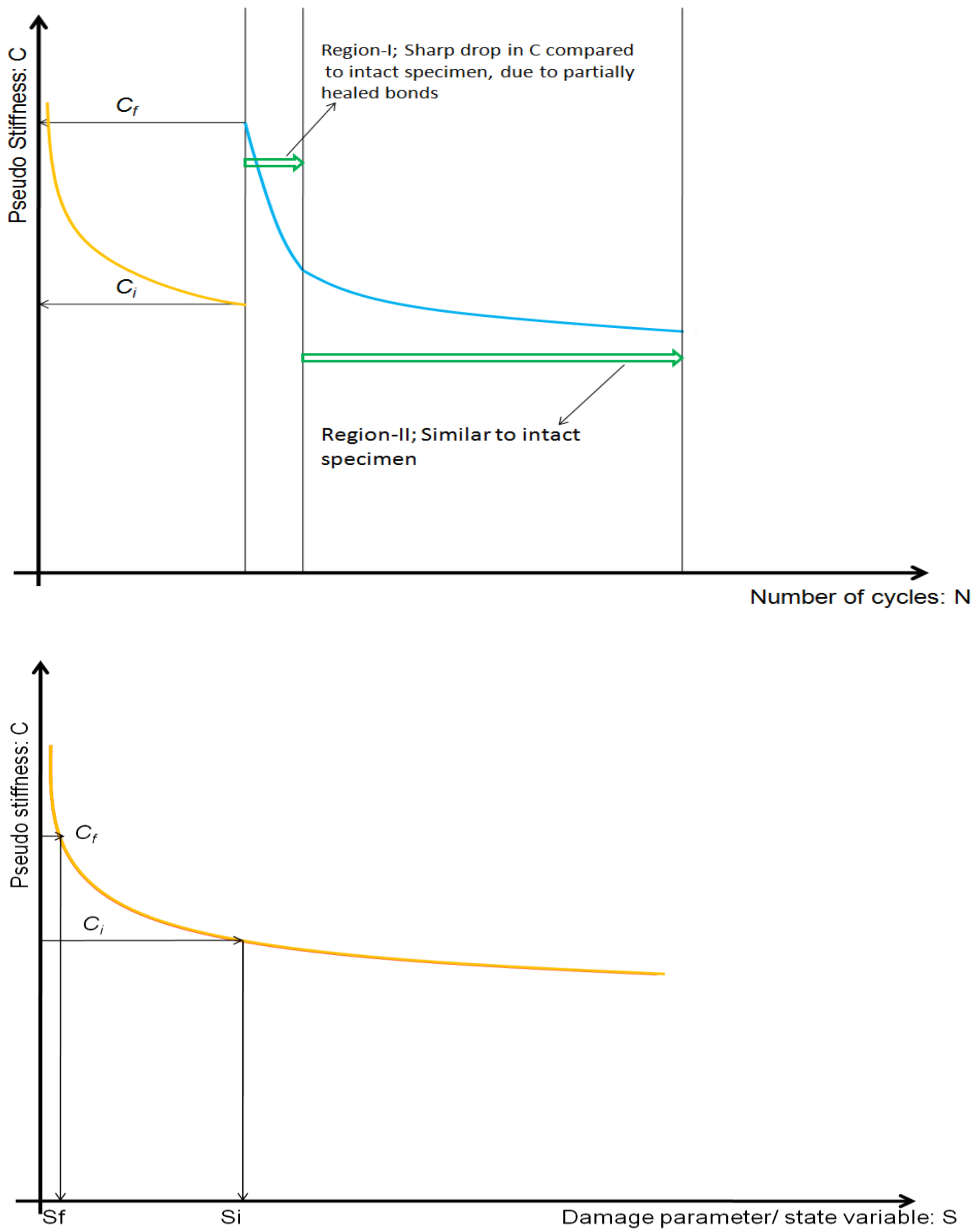

Figure 10: Schematic of typical Cvs.N before and after rest periods (top) and resulting underestimated value of $S_f(C,t)$using the characteristic $C(S)$ for the material (bottom)

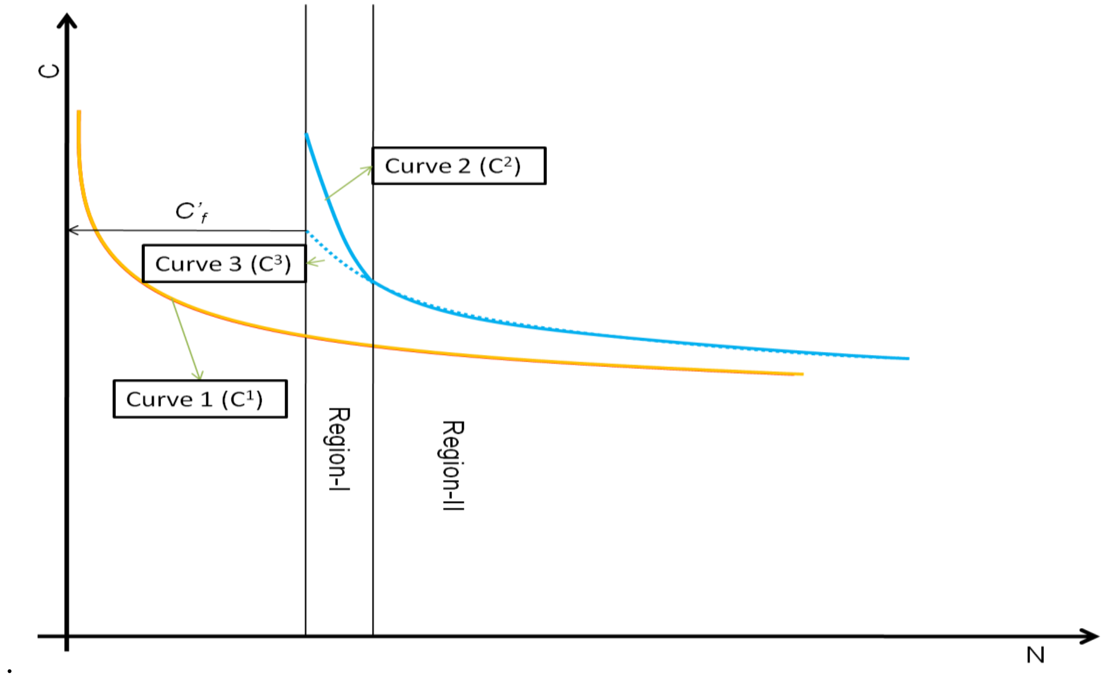

Figure 11: Actual and modified C-vs.-N curve represented by curve 2 and curve 3

3.2.3.4 Experimental procedure to quantify fatigue damage and healing

Based on the general methodology to quantify healing, the following test protocol was used to obtain the healing characteristics of the FAM mixes. A test specimen was subjected to cyclic torsion following a sinusoidal form with stress amplitude of 220 kPa and a frequency of 10 Hz. The test was continued until the specimen reached a predefined fraction of its initial stiffness. At this time, the specimen was allowed to rest devoid of any loads for a predefined duration of time. The load application was commenced immediately after the rest period until the specimen reached the next predefined level of stiffness and so on. The predefined levels of stiffness used in this study were $0.8C_1$, $0.7C_1$, and $0.6C_1$ where C_1 is the initial undamaged pseudo stiffness of the specimen. This procedure was used with four different specimens; each specimen being subjected to a different duration of the rest period. The rest periods used in this study were 5, 10, 20 and 40 minutes. Figure 12 illustrates a schematic of the load sequence for a specimen with a

5-minute rest period that was introduced at different fractions of its initial stiffness. Each test specimen provides a measure of healing as a function of the level of pseudo stiffness prior to a given duration of the rest period. By combining results from different specimens subjected to different durations of the rest period it is possible to obtain the healing characteristics of the mix. At least two replicate sets of four specimens each were tested following the above procedure.

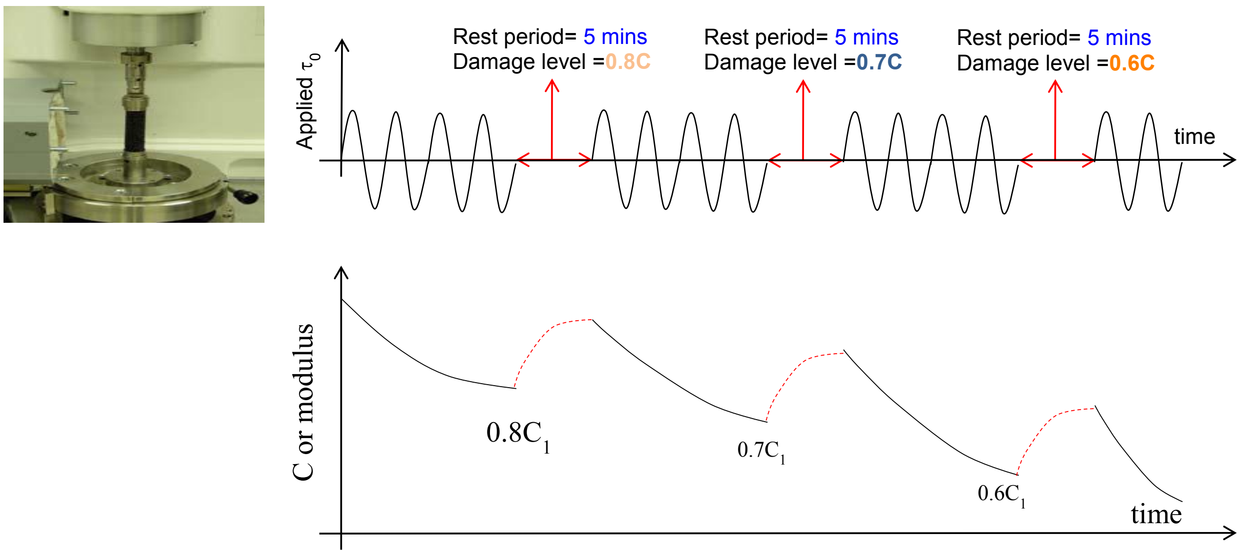

Figure13: Test protocol used to characterize healing as a function of pseudo stiffness

Note: (i) The dotted line was not measured – this is only a speculated increase in the pseudo stiffness over time. (ii) The figure illustrates a typical test with 5-minute rest period; tests with different rest periods follow a similar protocol.

3.2.3.5 Analytical steps to quantify healing

This section presents additional details on the analysis that was carried out with the data obtained from the experiments to determine $\%H(C,t)$ following the methodology described in Section 3.2.3.3. Four sets of data were obtained from the cyclic fatigue tests, each set corresponding to a different duration of the rest period. The stress and strain were converted to pseudo variables using an approximate method (Kutay, 2007) wherein,

Pseudo stress $\sigma^R=\sigma^o$ (26)

Pseudo strain $\epsilon^R = \epsilon^o * G^*lve$ (27)

Pseudo stiffness $C = \frac{G^*}{G^*_{lve}}$ (28)

In this study, the aforementioned approximate method yielded reasonable results and the characteristic $C(S)$ function was independent of the test method. However, a more robust method that involves complete integration of the first few cycles to obtain the pseudo variables (Schapery (1981)) will also be investigated in future work.

A power law function was then used to fit the measured C vs. N before the rest period as shown in Equation 29.

$$C^1 = A_1 - A_2 * (N)^r \tag{29}$$

where A_1,A_2 and r are model parameters.

The power law parameters from Equation 29 were then used with the data from Region II and Equation 30 to determine the horizontal shift, R, in the healing characteristics of the material following the rest period.

$$C^3 = A_1 - A_2 * (N - R)^r \tag{30}$$

C_i and C'_f were determined by using the value of N at which the rest period was introduced with Equations 29 and 30, respectively. Once the values of C_i and C'_f were known, the values of $S_i(C)$ and$S_f(C,t)$ were back-calculated from the $C(S)$ function for the material. Finally, these values were used with Equation 25 to compute $\%H(C,t)$.

Chapter 4: Results and Analysis

Using the experimental procedures outlined in Chapter three, the intrinsic healing in asphalt binders and overall healing in fine aggregate mastic (FAM) asphalt specimen were measured. Results obtained for intrinsic and overall healing are presented in this chapter as two sections, and both the sections includes a brief discussion on the important trends observed in the results.

4.1 INTRINSIC HEALING

Intrinsic healing in three different binders was measured at different temperatures and aging conditions (Section 3.1.3) using the procedure outlined in section 3.1.4 and the results obtained are presented below.

The measurements for intrinsic healing were carried out for 60 minutes. Three replicates of the two-piece specimen and single piece specimen, each were used to measure the complex shear modulus at thirteen different points in time. Intrinsic healing was computed as the average of the nine possible ratios of the three replicate measurements of complex shear modulus using the two-piece specimen to the three replicate measurements of complex shear modulus using the single piece specimen at any given point in time. In addition to the average percentage of intrinsic healing at any given point in time, the width of the 95% confidence interval was also computed at each time. Table 1 presents the width of the 95% confidence interval for the percentage healing at 60 minutes.

Table 1: Width of 95% confidence interval for percentage healing at 60 minutes

Temperature→ (°C)		10		15		20		25		30	
		% Healing	95% CI width	% Healing	95% CI width	% Healing	95% CI width	% Healing	95% CI width	% Healing	95% CI width
PG 64-22	RTFO	78.4	2.4	86.8	3.2	95.4	3.3				
	PAV					74.6	1.3	86.2	1.2	91.7	1
PG 70-22	RTFO	77.6	0.7	81.7	1.7	83.6	1.8	93.6	1.9		
	PAV					71.7	1.2	76.7	1	82.1	0.6
PG 76-22	RTFO			56.3	1	67.5	1.1	8.61	0.8		
	PAV					60	0.5	68.4	0.2	72.5	0.2

Note: Blank cells indicate that measurements were not made for that particular combination of aging and temperature.

From Table 1 it can be seen that, the width of the confidence interval is typically around 1 to 3% and it can be inferred from these results that the DSR based test procedure adopted to quantify intrinsic healing is repeatable. Also, the consistency in the measurements demonstrates that the trends in the intrinsic healing captured using this method is the true representative of the asphalt binder’s propensity to heal.

4.1.1 Material constants for the intrinsic healing function

The modified form of Avrami equation (Equation 3) was used to characterize the intrinsic healing function of the asphalt binder. Equation 3 represents the sum effect of (i) instantaneous strength gain due to interfacial cohesion at the crack interface, represented by the parameterR_o and (ii) time dependent strength gain due to rearrangement and randomization of molecules across the crack interface, represented by$(1 - R_o)(1 - e^{-qt^r})$ the parameter $q$is a temperature dependent material constant. The parameter r is a material constant that is used to represent the nature of internal transformation in metals or polymers. Traditionally, this parameter has been assigned an integer value between 1 and 4 for metals, whereas in the case of polymers the value of r can be a non-integer depending on the types of changes that may occur within the internal structure of the polymer. Accordingly, in this case the parameter q was treated as a temperature dependent material constant and the parameter r was treated as a material constant. For a given binder and aging condition, the data for different temperatures were combined to obtain the parameters R_o and q at each temperature while the parameter r was kept constant for a given material at all temperatures.

The model parameters for each asphalt binder and aging condition (R_o and q for each temperature and r) were determined using the Excel solver® with simultaneous regression of all the data that were obtained at different temperatures. Specific options were selected with the solver to ensure a robust estimation of the parameters: the conjugate gradient convergence as algorithm for search (this was to maximize global convergence by performing a larger number of iterations), central derivative scheme for iterations (this was to ensure no loss of curvature at points where the data shows rapid changes in slopes) and quadratic estimates for approximations (this option helps in tackling non-linear models). Figure 13 illustrates the typical data fitted to Equation 3 for the intrinsic healing of a PG 64-22 binder after long-term aging. Figure 14 illustrates the typical intrinsic healing characteristics for two other unaged asphalt binders at 25°C. A comparison of Figures 13 and 14 qualitatively illustrates the reduction in the contribution of time dependent intrinsic healing due to aging of asphalt binders.

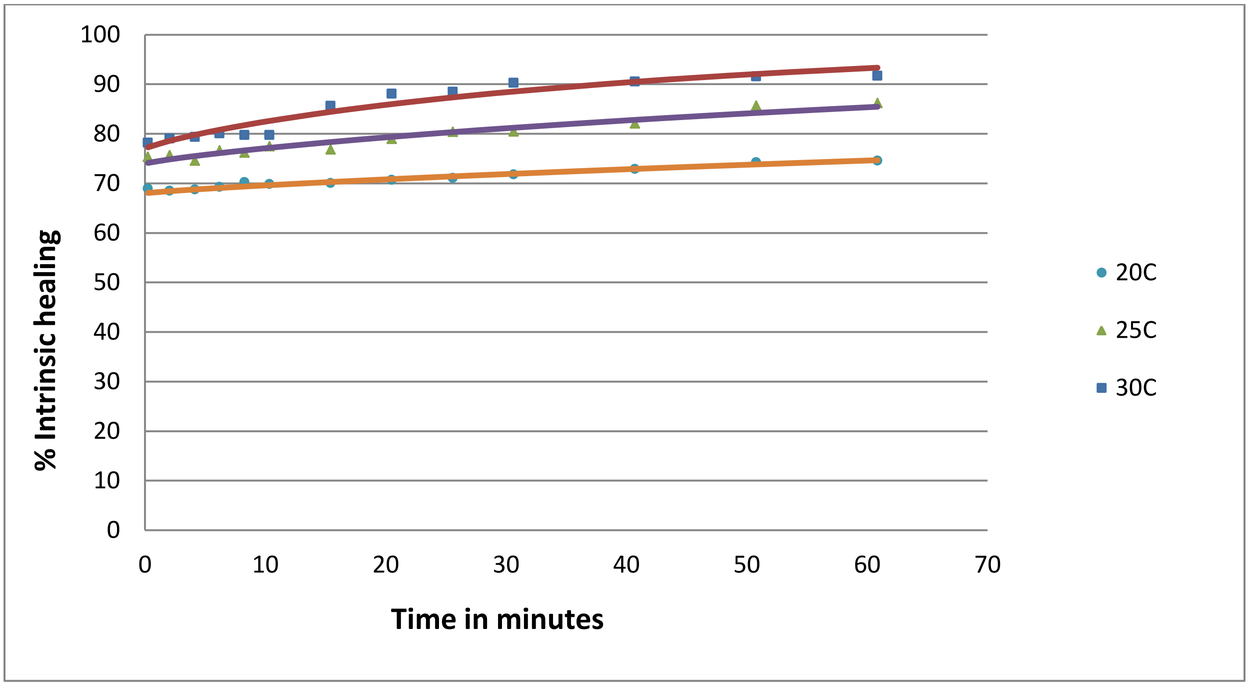

Figure 13: Typical rate of intrinsic healing for PAV aged PG 64-22 binder at different temperatures

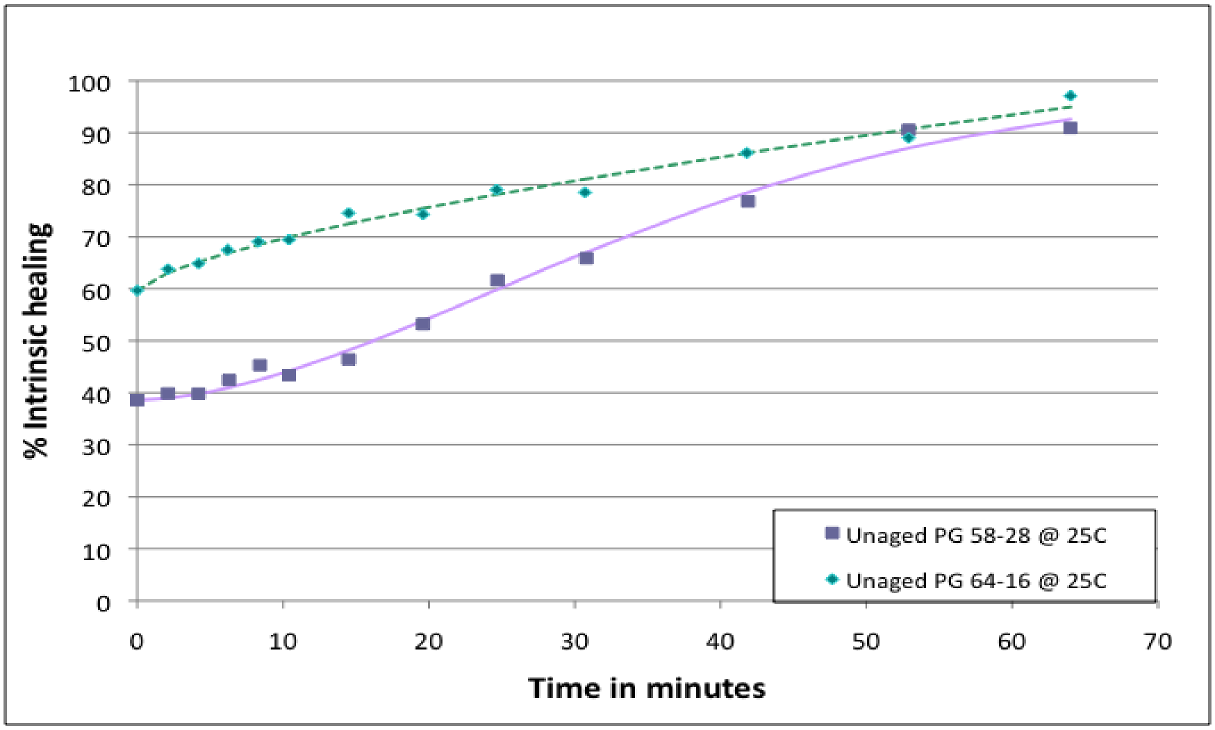

Figure 14: Typical rate of intrinsic healing for unaged binders at 25°C

Table 2 presents a summary of all the parameters for the intrinsic healing of RTFO and PAV aged binders at different temperatures. Figures 15 through 17 illustrate the change in the two key parameters R_o and q as a function of temperature and aging.

Table 2: Summary of model constants for the intrinsic healing function

Binder grade	Temp. (°C)	RTFO aged				PAV aged			
		R_0	q	r	90% healing (hours)*	R_0	q	r	90% healing (hours)*
PG 64-22	10	71	0.146		432				
	15	79	0.198		14				
	20	91	0.380	0.20	0	68	0.007	0.84	7
	25					74	0.018		2
	30					77	0.039		1
PG 70-22	10	73	0.017		22				
	15	77	0.018		15				
	20	79	0.023	0.57	8	69	0.007	0.63	51
	25	78	0.111		1	72	0.015		14
	30					77	0.020		7
PG 76-22	10	53	0.002		15				
	15	61	0.003		8				
	20	76	0.009	1.02	2	59	0.005	0.35	194567
	25					67	0.007		44739
	30					72	0.012		7448

Note: Blank cells indicate the measurements were not made at those temperature and aging conditions.

* Extrapolation based on Equation 3 and parameters shown in this table

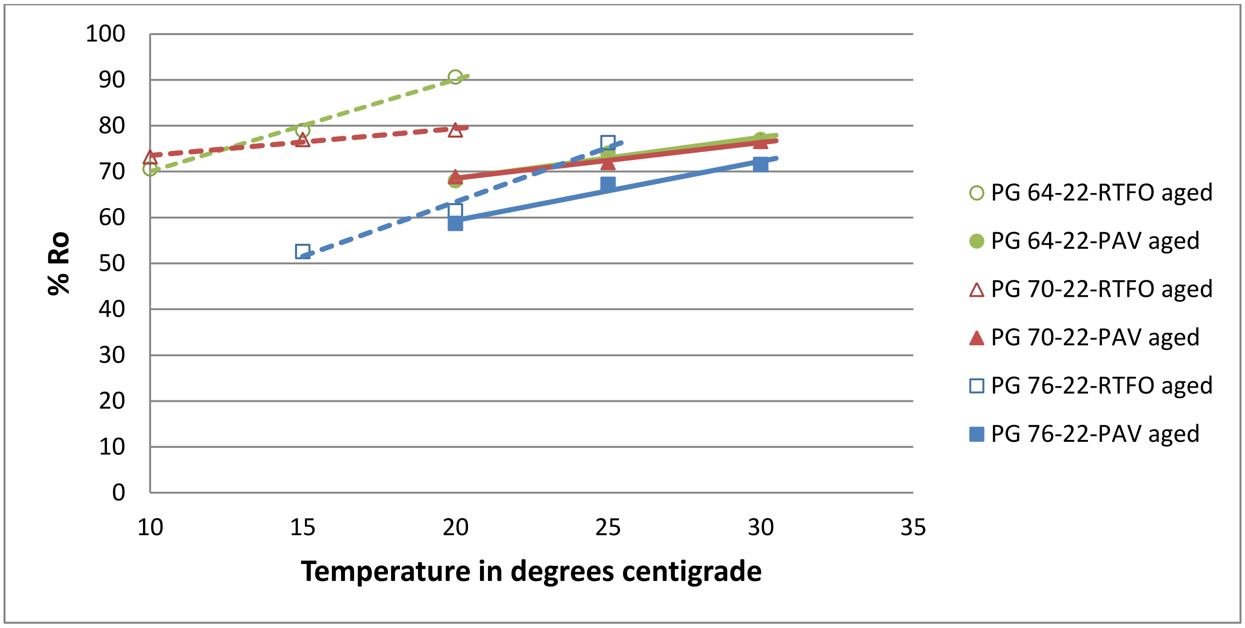

Figure 15: R_o for RTFO and PAV aged binders as a function of temperature

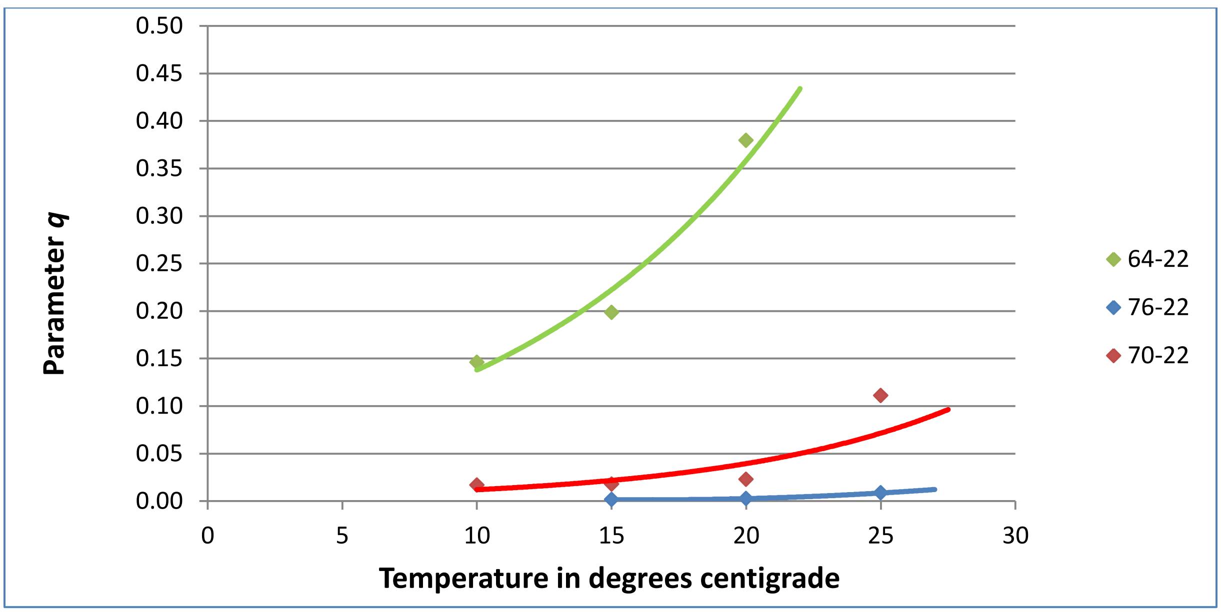

Figure 16: Parameter q for RTFO aged binders as a function of temperature

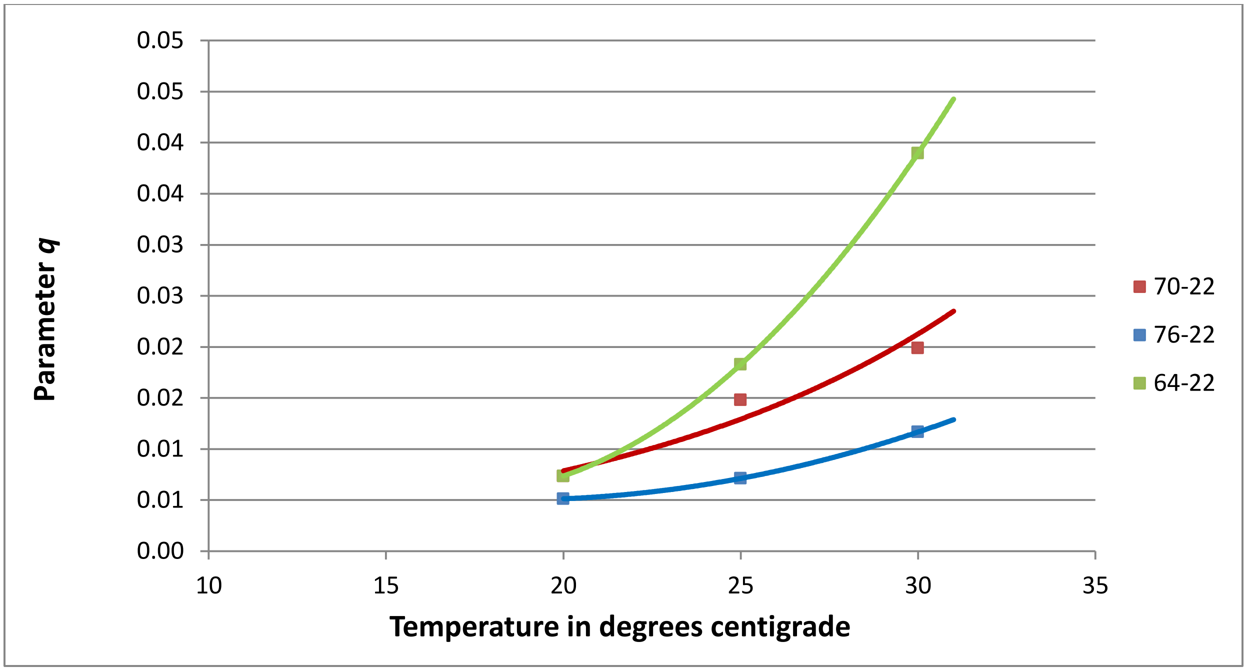

Figure 17: Parameter q for PAV aged binders as a function of temperature

Based on the hypothesis for intrinsic healing of asphalt binders, the initial healing is primarily governed by the interfacial cohesion between the crack faces. Also, time dependent healing is attributed to re-orientation and randomization of the molecules across the crack interface. Accordingly, the parameter R_o mostly reflects the instantaneous work of cohesion and theoretically it must not vary significantly within the range of temperatures used in these tests. Due to experimental limitations, this parameter also reflects the effect of interactions across the wetted interface that may occur during the short span of time between bringing the specimen faces into contact with each other and starting the test. Figure 15 illustrates the change in R_o with an increase in temperature. The parameter q reflects the temperature dependent intrinsic healing or rate of strength gain that is hypothesized due to the re-orientation and randomization of molecules across the interface. Figures 16 and 17 clearly show a strong relationship between

q and the test temperature for the RTFO and PAV aged binders. As one would expect, the parameter q increases with an increase in the test temperature.

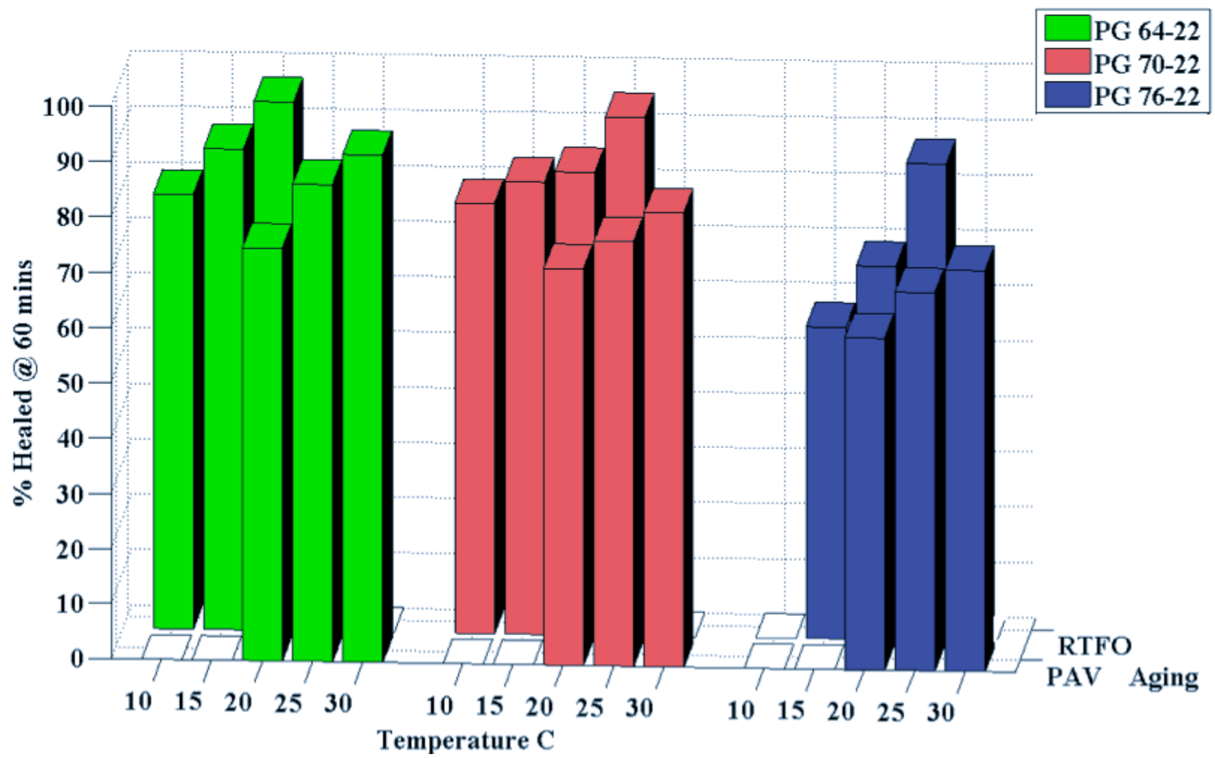

Figure 18: Total intrinsic healing at 60 minutes as a function of temperature and aging

Finally, Figure 18 illustrates the percentage of healing at the end of 60 minutes for the three different binders at different temperatures and aging conditions. As expected, an increase in temperature resulted in improved intrinsic healing after 60 minutes. Similarly, the overall intrinsic healing decreased due to aging of the asphalt binder. Despite the reduction in the overall healing of asphalt binder due to aging, the asphalt binders did demonstrate a significant capacity to regain stiffness at the end of 60 minutes. For example, stiffness of the two-piece specimen of a PAV aged PG 76-22 binder was approximately 60% of the stiffness of the single piece specimen after 60 minutes at 20 °C. However, it is important to note that this reflects only the intrinsic healing capacity of the asphalt binder. The overall ability of an asphalt binder to heal depends on the ability of the binder to reverse and close micro-cracks within the composite as well as the inherent capacity of the asphalt binder to regain strength. Consequently, the 60% gain in stiffness in the aforementioned example is the maximum self-healing capacity of the asphalt binder after a 60 minute rest period considering that the micro-cracks are completely and instantaneously reversed immediately after formation. In asphalt composites, this maximum capacity is reduced to varying degrees depending on the magnitude of damage prior to the rest period and mixture stiffness and viscoelastic properties that dictate the rate of crack wetting.

4.2 OVERALL HEALING

Using the experimental and analytical procedure listed in Sections 3.2.3.4 and 3.2.3.5., the percentage healing was calculated for the four different FAM mixes. The percentage healing is a function of the pseudo stiffness at which the rest period was introduced as well as the duration of the rest period. A function of the form presented in Equation 31, was used to describe the percentage healing as a function of rest period for each damage level at which the rest period was introduced.

$$\%\, Healed = m_1 * (1 - \exp(-m_2 * t)) \tag{31}$$

Figures 19 through 22 illustrate the final results for the percentage healing as a function of the rest period and pseudo stiffness (or level of damage) immediately preceding the rest period. The variability of percentage healing measured using the two replicates was reasonable considering the typical variability associated with fatigue tests. The results clearly show that, as expected, longer rest periods introduced at a similar level of damage (or pseudo stiffness) translate into a higher healing. Also, a higher percentage of healing is achieved when the rest periods are introduced at lower levels of damage (or higher relative pseudo stiffness) in the specimen. The following are two important observations. First, the variability between replicates for percentage healing was higher at higher levels of damage. In fact, many research studies consider a material as failed when it reaches 50% of its initial stiffness or *0.5C* in this case. Second, fitting the model in Equation 31 results in an asymptotic value of percentage healing that is less than 100% with the asymptotic value being smaller at higher levels of damage. This could indicate that complete healing may not be possible after a certain level of damage. The values of the asymptote being less than 100% could also be partially attributed to fitting the model with data extending only up to 40 minutes of rest period. It is therefore recommended to investigate healing characteristics at higher fractions of pseudo stiffness when the specimen is less damaged and for longer durations of rest periods.

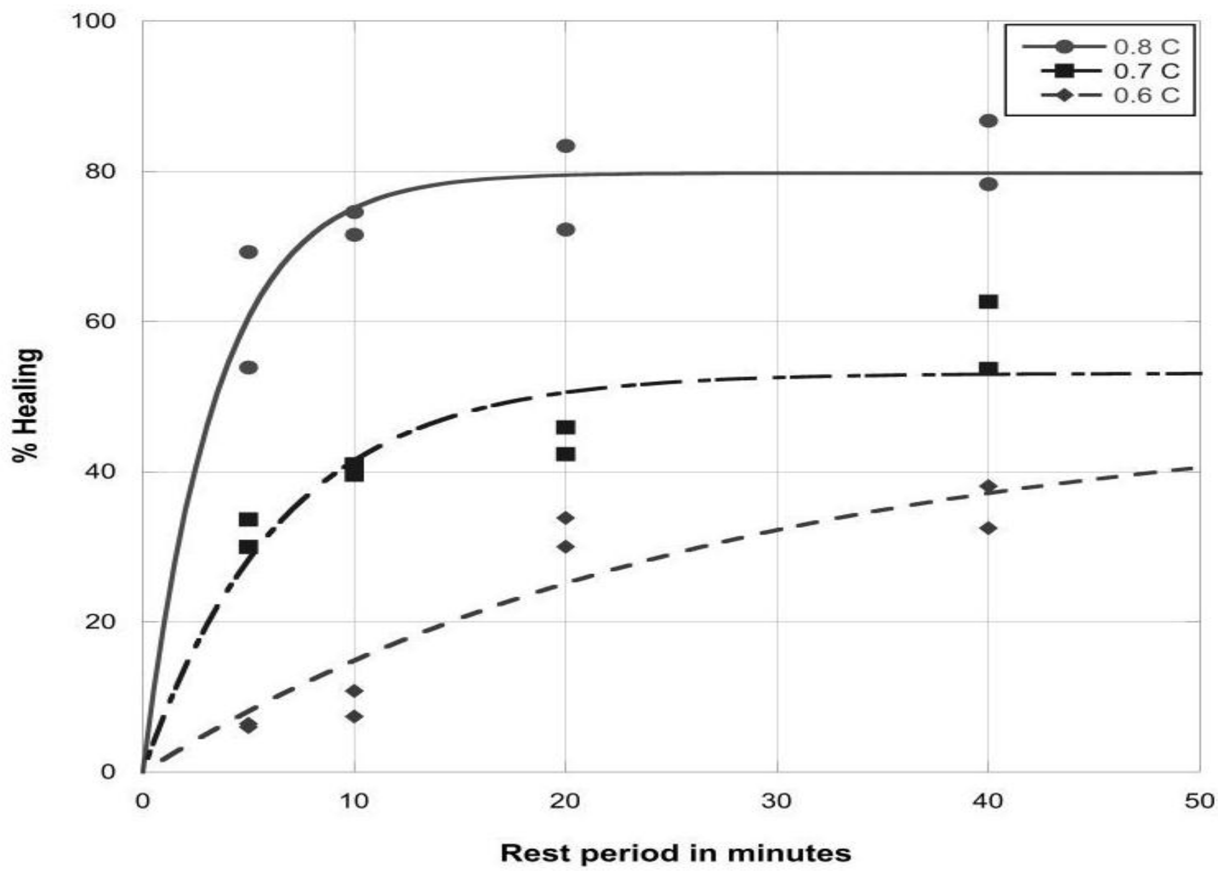

Figure 19: Percentage healing in FAM mix 12-64-16.

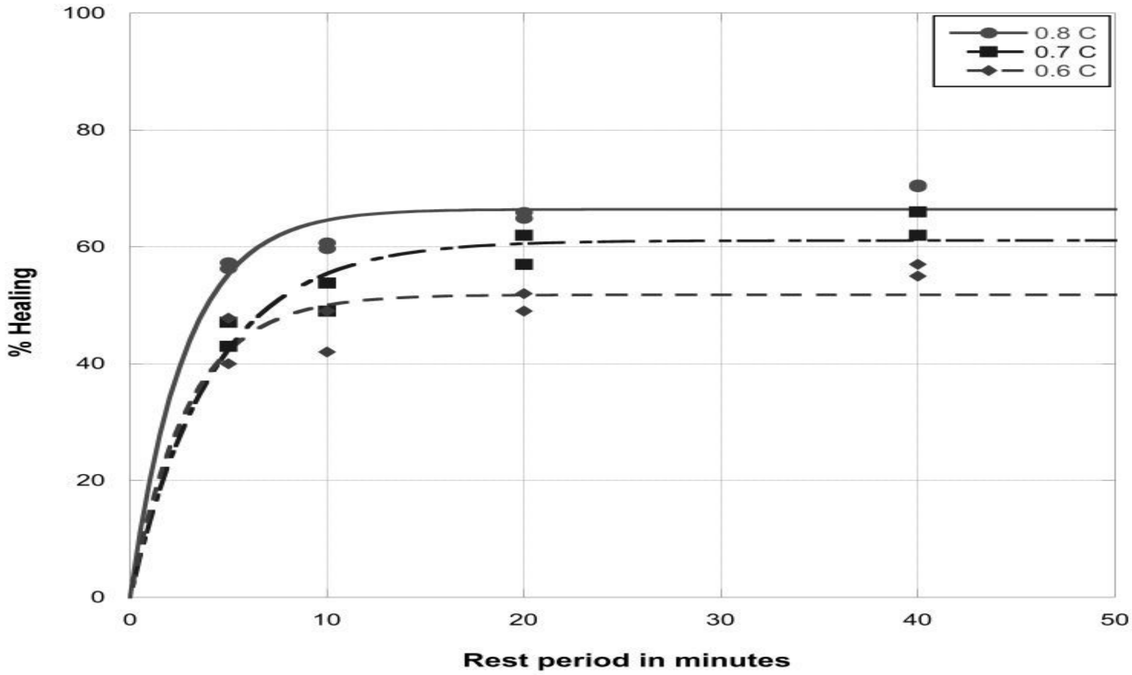

Figure 20: Percentage healing in FAM mix 12-67-22

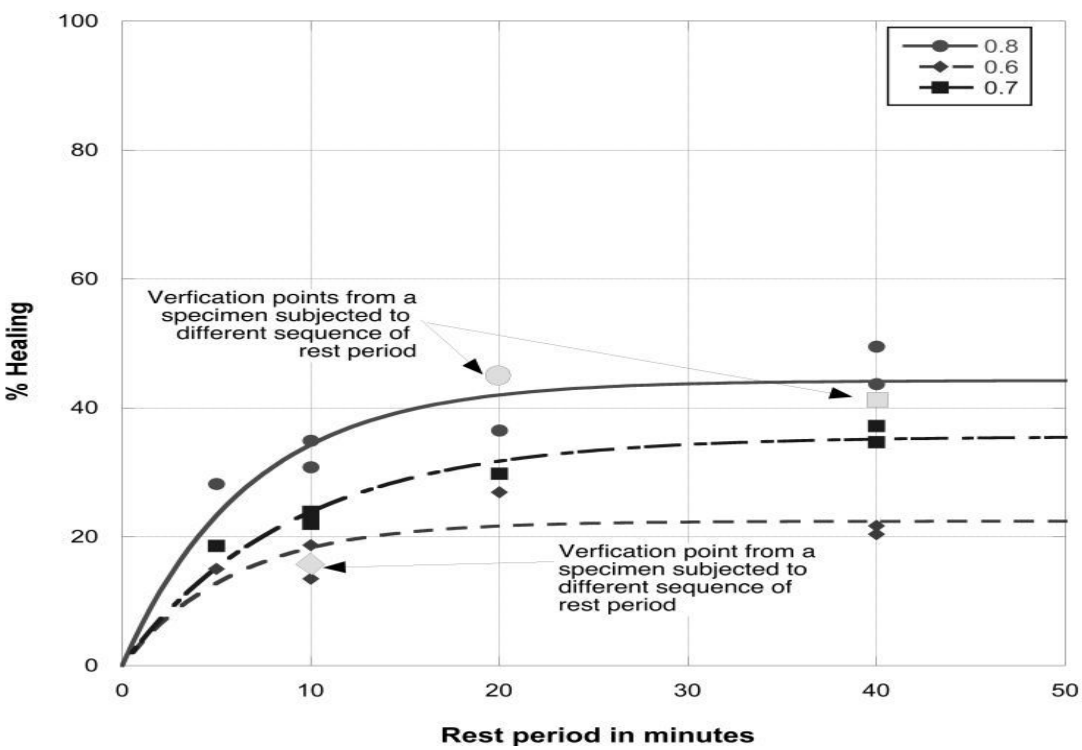

Figure 21: Percentage healing in FAM mix 10-67-22 and verification tests

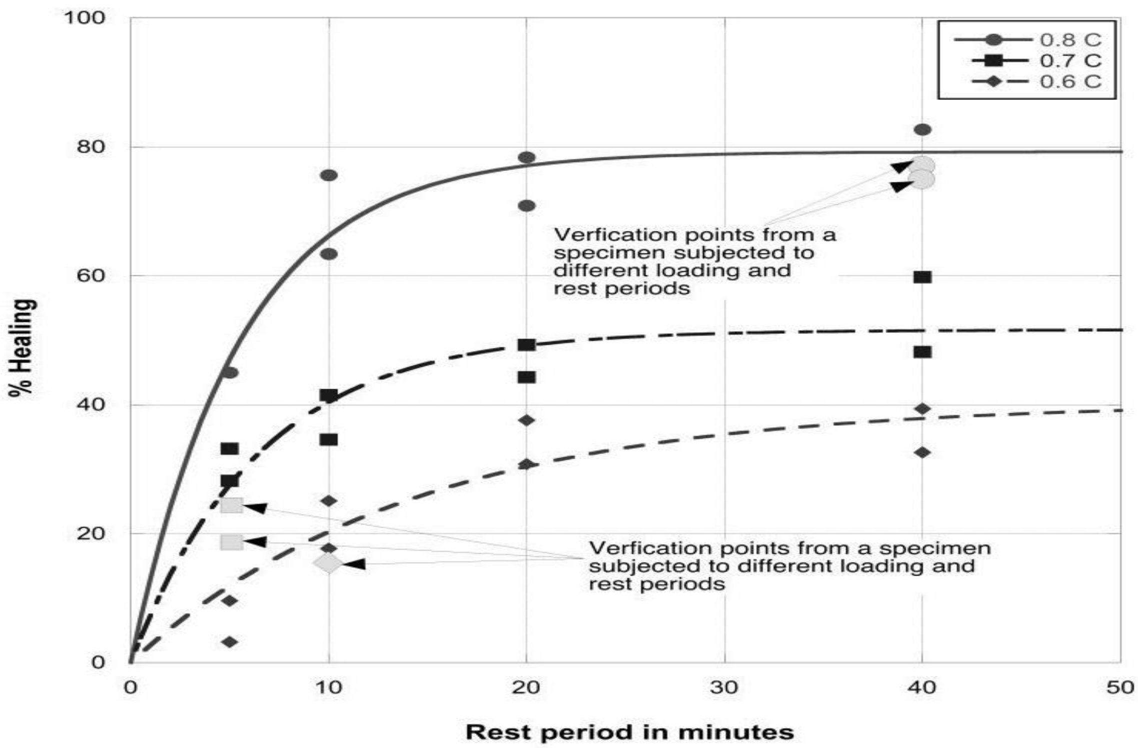

Figure 22: Percentage healing FAM mix 10-64-16 and verification tests

4.2.1 VERIFICATION TESTS FOR OVERALL HEALING

The first step was to verify that the percentage healing measured for a specific combination of rest period and damage level is unique irrespective of the sequence in which the rest periods were introduced during the test. To achieve this, fatigue tests were conducted on a test specimen of the 10-67-22 mix. Rest periods of 20, 40 and 10 minutes were introduced at 0.8, 0.7 and 0.6 C, respectively. Note that this sequence of rest period and damage level was completely different from the protocol described in Section 3.2.3.4. Figure 21 illustrates that the percentage healing computed from this verification test was reasonably close the expected values measured following the procedure in Section 3.2.3.5

The second step was to verify that the percentage healing measured for a specific combination of rest period and damage level is unique irrespective of the mode of loading that was used to induce fatigue damage to the specimen. To achieve this, fatigue tests were conducted on test specimens of the 10-64-16 mix. The tests were conducted by applying cyclic loads with a constant stress and constant strain amplitude. Figure 22 illustrates that the percentage healing from these tests were reasonable compared to the previously measured and expected values.

Chapter 5: Discussion and Conclusions

This chapter is divided into two sections and each section presents several conclusions that can be inferred from the results obtained from intrinsic and overall healing tests. Also each section includes a general discussion on the possible impacts these conclusions have in a broad scheme along with recommendations to enhance the process to (1) improve accuracy and (2) better address user defined problems.

5.1 INTRINSIC HEALING

At a micrometer length scale, the hypothesized mechanism for self-healing in asphalt binder within the asphalt composite entails the reversal of micro-cracks (or crack wetting) followed by strength gain over time (or intrinsic healing). Other models at the nanometer length scale describe the molecular origins of healing while models at the millimeter and larger length scale quantify the overall influence of self-healing in a continuum. The proposed mechanism can be used in conjunction with fracture mechanics to describe and model the micro-mechanics of crack growth and self-healing in asphalt composites. Based on previous research, the rate of crack wetting is dictated by crack size, crack geometry, properties of the asphalt binder, and viscoelastic properties of the composite. On the other hand, the rate of strength gain or intrinsic healing is dictated by the properties of the asphalt binder.

This study presents the use of a dynamic shear rheometer (DSR) to determine the rate of intrinsic healing of asphalt binders as influenced by aging and temperature. The test method was modeled after a similar approach used to determine the change in interfacial properties of polymers using the DSR. Important implications related to these measurements are listed below.

- Measuring the intrinsic healing characteristics of different asphalt binders is an important material property input to predict self-healing using the proposed mechanism. It is also an efficient tool by which to quantify the rate and healing capacities of different asphalt binders.
- The instantaneous intrinsic healing or fraction of stiffness gained immediately following wetting was significant for most of the binders used in this study. In most cases, the instantaneous strength gain decreased slightly with aging and increased with temperature.
- The time dependent intrinsic healing or fraction of stiffness gained over time following wetting was very strongly influenced by age and temperature. The time dependent increase in stiffness increased with temperature and decreased with aging.
- Although the inherent healing capacity of PAV aged binders was less than that of the RTFO aged binders, overall, even stiff PAV aged binders showed significant intrinsic healing (60% to 70%) after 60 minutes. This suggests that the effect of self-healing can be significant even for aged asphalt binders, provided that adequate wetting can be achieved (e.g. by limiting and dispersing the size of the micro cracks).

Apart from the aforementioned conclusions, it is also important to note that from the results presented in Chapter 4, the parameter q and parameter R_o are sensitive to temperature/aging and work of cohesion respectively. These paramters can be treated as a material property. It is speculated that these results are important as they can be used to characterize intrinsic healing over a range of temperature/aging conditions, while only performing a limited number of tests with the objective of indentifying these parameters. Although no attempts were made in this study, an exercise for future would be to use mathematical models to predict the intrinsic healing properties at different aging and temperature conditions. In other words it is proposed that a protocol similar to master curve generation to indentify modulus can be developed to predict the intrinsic healing response of the binder.

Another important aspect which can be included in the scope for future work would be to develop a new shear strength based test procedure to quantify healing. It is sometimes argued that healing measured as an increment in linear viscoelastic complex modulus cannot be a true representative of the strength gain as it is likely for the value of healing thus measured to be over predicted. In order to account for this important aspect, development of a new procedure to quantify intrinsic healing based on the shear strength of the healed interface instead of using dynamic modulus is recommended.

5.2 OVERALL HEALING

This thesis presented an experimental and analytical method to quantify healing in FAM mixes as a function of the duration of rest period and the level of damage preceding the rest period. The analytical method was based on the elastic work potential theory and the viscoelastic continuum damage approach that was originally developed to characterize fatigue cracking in full asphalt mixtures. The method was applied to four different FAM mixes. The healing characteristics obtained using this method clearly demonstrate the influence of factors such as binder type, binder content, duration of rest period and level of damage preceding the rest period on overall healing. More importantly, two different verification tests were conducted to demonstrate that the percentage healing measured using the proposed method can be treated as a characteristic material property. In other words, preliminary results indicate that this approach can be used to obtain a unique healing characteristic function for the material. It must also be noted that although this method was developed for FAM specimens, it could also be extended and applied to full asphalt mixtures.

It was found that higher binder content FAM specimen generally displayed a higher percentage of healing when compared to similar grade lower binder content FAM specimen at any damage level and for any duration of rest period. Also it was found that the values of percentage healing quantified were sensitive to difference in binder grade, as the stiffer binder exhibited lesser percentage healing and vice versa. It is important to note that the differences in overall healing obtained due to differences in stiffness of the binder can be explained based on the intrinsic healing behavior of the binder. The first module of this research on intrinsic healing clearly demonstrated such similar trends.

As illustrated earlier in Chapter 4, overall healing measured at higher damage levels was significantly lower (usually around 10 to 20 percent) when compared to lower damage levels. In addition, not much improvement was noted with an increment in the duration of rest period provided at high damage levels. This trend indicates that significant overall healing cannot be achieved if the amount of damage is high, this is in agreement with the contention that a distribution of micro-cracks provides a more congenial condition to heal when compared to a body with a distributed set of macro-cracks. Although it would be premature to pinpoint the exact reason for such behavior, on a nanometer length scale, it can be speculated that the forces that drive the mechanism are essentially surface forces and these surface forces will be dominant if the two crack surfaces are close to each other.

This method can be used with full asphalt mixtures to estimate a general distribution of cracks and their respective size corresponding to the loss in the pavement's ability to self-heal. Such predictions are useful in many aspects of pavement maintenance and design as they have the following advantages:(1) scheduling remedial measures to extend the pavement life, (2) developing a design protocol which can accommodate healing and predict the rate at which fatigue damage accumulates and (3) provide a parameter to differentiate the performance of different asphalt mixtures.

In light of the results obtained the following recommendations are made as the scope for future work:

- The current study evaluated overall healing at 25 $°C$ and short term ageing conditions. Additional tests can be conducted at different temperatures and aging conditions to convert the present isothermal model to a more consummate model with the ability to predict healing over a wider range of temperatures and aging conditions.
- The relationship between percentage drop in S and gain in number of load cycles can be developed as a function of strain level, as it is preferred to gauge the fatigue life of pavement as the number of load cycles required until failure.
- More validation tests which include a higher degree of randomization in terms of duration, damage level, mode and amplitude, can be conducted to emphasize that the VECD theory is successful in predicting overall healing as a material property.
- Correspondence principles based on the undamaged nonlinear constitutive viscoelastic behavior of the material can be incorporated into the analysis procedure, as it is speculated that fatigue damage represented as the material behavior deviating from nonlinear viscoelastic behavior as opposed to deviation from linear viscoelastic behavior, may be a closer representative of phenomena occurring in the field.
- It is expected that binders with similar performance grading but with different chemical composition will exhibit different trends in healing. To account for the chemical composition another parameter apart from duration of rest period and damage level can be introduced into the overall healing model.

- Finally, the procedure can be further simplified using some regression tools to develop the healing potential by minimizing the amount of testing required, as it could serve as an important aid for the designers to have a database of healing functions for different types of mixes in use.

Appendix : Gradation Table Used For FAM Mixes

		BIN FRACTIONS										
		Bin No.1		**Bin No.2**		**Bin No.3**		**Bin No.4**				
Aggregate Source:		Hanson		Hanson		Hanson		Hanson				
Aggregate Number:		Type C		F Rock		Washed Screening		Sand				
Sample ID:												
Rap?, Asphalt%:										Total Bin		
Individual Bin (%):		30.0	Percent	36.0	Percent	24.0	Percent	10.0	Percent	100.0 %	Lower & Upper Grade Specification Limits	
Sieve Size:	Sieve Size: (mm)	Cum. % Passing	*Wtd* Cum. %	Cum. % Passing	*Wtd* Cum. %	Cum. % Passing	*Wtd* Cum. %	Cum. % Passing	*Wtd* Cum. %	Cum. % Passing		
1"	25.000	100.0	30.0	100.0	36.0	100.0	24.0	100.0	10.0	100.00	100.0	100.0
3/4"	19.000	98.7	29.6	100.0	36.0	100.0	24.0	100.0	10.0	99.60	95.0	100.0
3/8"	9.500	21.5	6.5	93.0	33.5	100.0	24.0	100.0	10.0	74.00	70.0	85.0
No. 4	4.750	3.4	1.0	65.3	23.5	99.4	23.9	97.4	9.7	58.10	43.0	63.0
No. 8	2.360	1.4	0.4	29.0	10.4	74.8	18.0	85.3	8.5	37.30	32.0	44.0
No. 30	0.600	1.3	0.4	8.9	3.2	40.0	9.6	64.5	6.5	19.70	14.0	28.0
No. 50	0.300	1.3	0.4	3.8	1.4	20.0	4.8	15.0	1.5	8.10	7.0	21.0
No. 200	0.075	1.0	0.3	3.6	1.3	3.6	0.9	2.5	0.3	2.80	2.0	7.0
	0.000		0.0		0.0		0.0		0.0	0.00		

Asphalt Source & Grade	PG 64-22	Binder content, (%)	4.400

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